Defense Threat Reduction Agency
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DTRA-TR-12-001

TECHNICAL REPORT

# Radiation Dose Assessments for Shore-Based Individuals in Operation Tomodachi

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September 2012

Prepared by:
Dose Assessment and Recording Working Group

For:
Assistant Secretary of Defense for Health Affairs

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| REPORT DOCUMENTATION PAGE | *Form Approved* **OMB No. 0704-0188** |
|---|---|



| **1. REPORT DATE** *(DD-MM-YYYY)* | **2. REPORT TYPE** | **3. DATES COVERED** *(From - To)* |
|---|---|---|
| 30-09-2012 | Technical report | |

**4. TITLE AND SUBTITLE**
Radiation Dose Assessments for Shore-Based Individuals in Operation Tomodachi

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
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**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
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**8. PERFORMING ORGANIZATION REPORT NUMBER**

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
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Fort Belvoir, VA 22060-6201

**10. SPONSOR/MONITOR'S ACRONYM(S)**
DTRA RD-NT

**11. SPONSORING/MONITORING AGENCY REPORT NUMBER**
DTRA-TR-12-001

**12. DISTRIBUTION AVAILABILITY STATEMENT**
DISTRIBUTION A. Approved for public release: distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
This report provides the radiation dose assessments for the Department of Defense shore-based population of interest that was potentially exposed to radioactive fallout resulting from the Fukushima Daiichi nuclear power station units' radiological releases that followed the earthquake and tsunami on March 11, 2011. The associated Department of Defense disaster relief operation to the citizens of Japan was entitled, "Operation Tomodachi." Finalized radiation dose assessments for the population of interest should be loaded into an Operation Tomodachi Registry by the end of 2012, which will support public inquiries.

**15. SUBJECT TERMS**
Operation Tomodachi, Radiation Dose, Department of Defense, Japan, Fukushima, Earthquake, Tsunami

| **16. SECURITY CLASSIFICATION OF:** a. REPORT | b. ABSTRACT | c. THIS PAGE | **17. LIMITATION OF ABSTRACT** | **18. NUMBER OF PAGES** | **19a. NAME OF RESPONSIBLE PERSON** |
|---|---|---|---|---|---|
| U | U | U | U | | Paul K. Blake, PhD |

**19b. TELEPONE NUMBER (*Include area code* )**
*703 767-3384*

# CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY → BY → TO GET
TO GET ← BY ← DIVIDE

| | | |
|---|---|---|
| angstrom | 1.000 000 x E -10 | meters (m) |
| atmosphere (normal) | 1.013 25 x E +2 | kilo pascal (kPa) |
| bar | 1.000 000 x E +2 | kilo pascal (kPa) |
| barn | 1.000 000 x E -28 | meter$^2$ (m$^2$) |
| British thermal unit (thermochemical) | 1.054 350 x E +3 | joule (J) |
| calorie (thermochemical) | 4.184 000 | joule (J) |
| cal (thermochemical/cm$^2$) | 4.184 000 x E -2 | mega joule/m$^2$ (MJ/m$^2$) |
| curie | 3.700 000 x E +1 | *giga bacquerel (GBq) |
| degree (angle) | 1.745 329 x E -2 | radian (rad) |
| degree Fahrenheit | $t_k = (t^o f + 459.67)/1.8$ | degree kelvin (K) |
| electron volt | 1.602 19 x E -19 | joule (J) |
| erg | 1.000 000 x E -7 | joule (J) |
| erg/second | 1.000 000 x E -7 | watt (W) |
| foot | 3.048 000 x E -1 | meter (m) |
| foot-pound-force | 1.355 818 | joule (J) |
| gallon (U.S. liquid) | 3.785 412 x E -3 | meter$^3$ (m$^3$) |
| inch | 2.540 000 x E -2 | meter (m) |
| jerk | 1.000 000 x E +9 | joule (J) |
| joule/kilogram (J/kg) radiation absorbed dose | 1.000 000 | Gray (Gy) |
| kilotons | 4.183 | terajoules |
| kip (1000 lbf) | 4.448 222 x E +3 | newton (N) |
| kip/inch$^2$ (ksi) | 6.894 757 x E +3 | kilo pascal (kPa) |
| ktap | 1.000 000 x E +2 | newton-second/m$^2$ (N-s/m$^2$) |
| micron | 1.000 000 x E -6 | meter (m) |
| mil | 2.540 000 x E -5 | meter (m) |
| mile (international) | 1.609 344 x E +3 | meter (m) |
| ounce | 2.834 952 x E -2 | kilogram (kg) |
| pound-force (lbs avoirdupois) | 4.448 222 | newton (N) |
| pound-force inch | 1.129 848 x E -1 | newton-meter (N-m) |
| pound-force/inch | 1.751 268 x E +2 | newton/meter (N/m) |
| pound-force/foot$^2$ | 4.788 026 x E -2 | kilo pascal (kPa) |
| pound-force/inch$^2$ (psi) | 6.894 757 | kilo pascal (kPa) |
| pound-mass (lbm avoirdupois) | 4.535 924 x E -1 | kilogram (kg) |
| pound-mass-foot$^2$ (moment of inertia) | 4.214 011 x E -2 | kilogram-meter$^2$ (kg-m$^2$) |
| pound-mass/foot$^3$ | 1.601 846 x E +1 | kilogram-meter$^3$ (kg/m$^3$) |
| rad (radiation dose absorbed) | 1.000 000 x E -2 | **Gray (Gy) |
| roentgen | 2.579 760 x E -4 | coulomb/kilogram (C/kg) |
| shake | 1.000 000 x E -8 | second (s) |
| slug | 1.459 390 x E +1 | kilogram (kg) |
| torr (mm Hg, $0^0$ C) | 1.333 22 x E -1 | kilo pascal (kPa) |

*The becquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.
**The gray (Gy) is the SI unit of absorbed dose.

**DTRA-TR-12-001: Radiation Dose Assessments for Shore-Based Individuals in Operation Tomodachi**

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## Acknowledgements

The authors gratefully acknowledge the support of the following individuals:

- Dr. Daniel Blumenthal, National Nuclear Security Administration, who shared DOE's radiological monitoring results.
- Dr. FURUTA Sadaaki, Japan Atomic Energy Agency, who provided information on the Japanese radiological monitoring stations.
- Veterans' Advisory Board on Dose Reconstruction, Subcommittee No. 1 members (Mr. Harold Beck, Mr. Paul Voilleque, and Dr. Gary Zeman), who provided a preliminary peer review.
- National Council on Radiation Protection and Measurements, Scientific Committee No. 6-8 members (Dr. John Till, Dr. John Boice, Dr. Iulian Apostoaei, and Mr. William Kennedy, Jr.) who provided follow-on peer review.
- Major Steven Dewey, USAF School of Aerospace Medicine, who provided valuable technical consultation.
- Dr. John Mercier of Tech 62, Inc., who provided technical consulting, and acted as an unofficial liaison with both DOE and the Japanese scientific community.
- Dr. David Kocher of SENES Oak Ridge, Inc., who provided peer review.
- Dr. Mondher Chehata of SAIC, Inc. who provided technical consultation and critical reviews of environmental monitoring data.
- Mr. Brian Sanchez of ARA, Inc., who designed and administered the M.S. SharePoint website that supported this effort.
- Ms. Hilda Maier, Mr. Hanson Gaugler, Ms. Debra Gross of L-3 Services, Inc., who provided logistics and computing support for this effort.
- Dr. Craig Postlewaite and Mr. Scott Gordon of the Office of the Assistant Secretary of Defense for Health Affairs, who provided enthusiastic support and critical guidance.

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# ES-1.

## Executive Summary

This report presents the results of radiation dose assessments for the Department of Defense (DOD) shore-based population of interest (POI) during the 60-day period from March 12, 2011 to May 11, 2011 following a 9.0 magnitude earthquake and resulting tsunami that damaged the Fukushima Daichi nuclear power station in Japan.

At 1446 Japan Standard Time[1] on March 11, 2011, a 9.0 magnitude earthquake, the largest ever recorded in Japan, occurred at a depth of approximately 19 miles, 80 miles east of Sendai and 231 miles northeast of Tokyo off the coast of Honshu Island (USGS, 2011). This earthquake resulted in the automatic shutdown of 11 nuclear power plants at four sites along the northeast coast of Japan (Onagawa 1, 2, and 3; Fukushima Daiichi 1, 2, and 3; Fukushima Daini 1, 2, 3, and 4; and Tokai 2).

On March 11, 2011, Fukushima Daiichi Nuclear Power Station (FDNPS) Units 1, 2, and 3 were in operation, and Units 4, 5, and 6 were shut down for routine refueling and maintenance activities; the Unit 4 reactor fuel was offloaded to the Unit 4 spent fuel pool. As a result of the earthquake, offsite power was lost to FDNPS. The emergency diesel generators started at all six units providing alternating current (AC) electrical power to critical systems at each unit.

During the following days plant workers strived to maintain control of the reactor facilities to maintain cooling of the shut-down reactors and spent fuel pits. Unfortunately, several events, such as explosions in certain buildings, rupture of total containment etc., resulted in the release of radioactive fission products from the plant. These releases continued sporadically at least until the end of March. Overall, significant amounts of radioactivity were released from FDNPS Units 1, 2, and 3 into the atmosphere as gases and aerosols and into the ocean through contaminated seawater that had been used for cooling the units (INPO, 2011). The released radioactive materials were transported by changing weather patterns to most of the island of Honshu and beyond, and deposited on lands, buildings, and water bodies.

The radiological events added to the disastrous effects of the earthquake and ensuing tsunami which resulted in the loss of thousands of lives, catastrophic damage to cities, towns and villages; dismantling of infrastructure, food and water supplies; and forced millions of Japanese citizens from their homes.

U.S. agency offices located in Japan, their workers and those aboard ship nearby faced adversity also. Overall, the nearly 70,000 individuals in the DOD-affiliated population (defined as Service members, civilian employees, family members of Service members and civilian employees, and contractor employees) were located at or near approximately 63 U.S. military

[1] Japan Standard Time (JST), 0000-2400, is used throughout this report, unless otherwise noted.. JST is 9 hours ahead of Coordinated Universal Time (UTC). DOD's use of UTC is traditionally noted by the "Zulu (Z)" designation; e.g. 1630Z.

facilities located on the four main islands of Japan (Hokkaido, Honshu, Shikoku, and Kyushu). Japan is divided into 47 sub-national jurisdictions known as prefectures, which are analogous to U.S. states. Approximately 50 percent of the U.S. military stationed in Japan are located in the Okinawa prefecture, which is not considered a main island. The potentially-affected U.S. military facilities are concentrated in a few prefectures, with 15 in Kanagawa, 10 in Nagasaki, and six in Tokyo.

The U.S. mobilized for humanitarian assistance / disaster relief (HADR) support to Japan, and to assess the status of its citizens. Operational reports indicated U.S. forces encountered radiation levels from apparent passing clouds of released radioactive materials. News media reports provided confirming articles. Four days after the earthquake and tsunami, the Chairman, Senate Veterans' Affairs Committee (SVAC) contacted the Secretary of Defense and expressed concerns that U.S. forces providing disaster response in Japan might be exposed to radiation and other environmental toxins (SVAC, 2011). The SVAC Chairman urged DOD to create a database of U.S. Service members supporting the relief effort in Japan to track data related to exposure to radiation and other environmental toxins. The Under Secretary of Defense for Personnel and Readiness (USD(P&R)) responded that DOD was working with the Department of Veterans Affairs (VA) to ensure that affected Service members were being appropriately monitored (USD(P&R), 2011).

Soon thereafter, the Assistant Secretary of Defense for Health Affairs (ASD(HA)) requested that the Army Institute of Public Health (AIPH) serve as the lead organization for the creation and operation of the Operation Tomodachi Registry (OTR) (ASD(HA), 2011a). Planning, development, and implementation activities required to establish the OTR were delegated to an OT Steering Committee and four working groups: the OTR Implementation Working Group (OTRIWG), the Dose Assessment and Recording Working Group (DARWG), the Population of Interest Working Group (POIWG), and the Medical and Claims Users Working Group (M&CUWG). Briefly, these four working groups would: 1) develop an approach to construct and sustain the OTR in a manner that will withstand scrutiny from the various stakeholders and Congress; 2) conduct dose assessments using all relevant data of sufficient data quality; 3) collect and organize once-daily personnel location data for all DOD affiliated personnel associated with OT; and 4) define OTR data needed to support claims adjudication, medical surveillance, and general health-related inquiries.

This report discusses the approach, methods, and results of a study to estimate conservative radiation doses that may be assigned to individuals who are part of a potentially exposed population (PEP). Radiation doses from releases of radioactive material from the FDNPS accident are calculated based on an assumed exposure period of 60 days from March 12, 2011 to May 11, 2011. This period represents the time during which DARWG evaluations indicated the major potential for exposure existed and ending when external radiation dose rates had decreased to levels associated with the radioactive decay of radionuclides with half-lives of several years or more.

The dose assessment process involved the collection and review of external radiation exposure rate information and radionuclide concentration results in air, water, and soil that were collected by various agencies of the DOD, the Department of Energy (DOE), the Government of Japan (GOJ) and others. Data were either used as reported or estimated using sound techniques for periods of time for which data were not available or when data were judged unreliable. These results were combined with very conservative values of exposure parameters, such as breathing

rate, water ingestion rate, uncertainties in dose coefficients for internal radionuclides, and others to produce doses that are considered to be higher than the dose received by any member of the POI. The methods account for exposure while performing at various levels of physical activity, whether indoors or outdoors, and for adults and children in six age ranges.

Assessments to produce credible estimates of the doses and their associated uncertainties are currently underway and are expected to support our view that these reported doses are greater than any individual's true dose. These doses reported herein are intended only to inform those who were in Japan during the time of the incident and should not be used for compensation decisions or studies on the medical effects of ionizing radiation exposures. Furthermore, additional technical reports are being prepared to address:

- Doses to shipboard personnel, aircrews and personnel who visited J-Village,
- Doses to an embryo or fetus from exposure to the pregnant woman, and
- Doses to nursing infants of mothers who may have inhaled or ingested radioactive materials from the FDNPS.

In this dose assessment, we calculated doses from sources outside the body and those inside the body. The main source of radiation outside the body includes radioactive materials in passing plumes and radioactive materials deposited on the ground. The sources of radiation inside the body are radioactive materials that deposit in tissues and organs after breathing air containing radioactive materials and ingesting water, food, and dirt that have been contaminated with radioactive materials. For external dose calculations, we used measurements of radiation dose rates at various locations where DOD-affiliated individuals worked and lived, and we used the results of personnel dosimeters for those who participated in humanitarian relief efforts, or who entered potentially contaminated areas. For internal dose calculations, we used measurements of radioactivity in the air, water, and soil combined with internationally accepted parameters for calculating dose. Over 8,000 individuals were monitored for internal radioactive materials and the results of those tests were compared with the calculated doses.

The quantities calculated in this report are whole body effective dose and thyroid dose as presented in ICRP Publication 60 (ICRP, 1991) and used in the ICRP databases of dose coefficients (DCs) (ICRP, 2001, 2003, and 2007b). The effective dose is a radiation protection quantity that allows external and internal doses to be combined to obtain an estimate of overall possible harm. Thyroid dose is the total dose to the thyroid gland from external and internal radiation, and is important in assessing the potential for thyroid disease. The effective dose and equivalent dose "provide a basis for estimating the probability of stochastic effects only for doses well below the threshold for deterministic effects" and "are intended for use in radiation protection, including the assessment of risk in general terms."

The doses calculated in the report were accomplished using very conservative estimates of the various parameters required to convert activity concentrations into dose. These overestimates are intended to produce doses that are theoretically possible but not likely to be received by any individual. To lend further support to the notion that these doses are higher than anyone is likely to receive, additional studies are underway to prepare best estimates of dose and the associated uncertainty using probabilistic methods. The results of those studies are scheduled for publication by the end of 2012.

Copious measurements of external dose rates, and activity concentrations in air, water, and soil were accomplished by DOD, DOE, and GOJ technical teams, and were collected, reviewed, and selected for use in these dose calculations. Whenever DOD and DOE sources of measurements contained data gaps, measurements from the Japan's Ministry of Education, Culture, Sports, Science, and Technology (MEXT) were used to fill those gaps to provide full coverage for every day during the 60-day period of concern. Similarly, 24-hour measurement of air concentrations at Yokota AB and the International Monitoring Station (IMS) at Takasaki, Gunma, Japan supplemented or replaced limited or lower quality measurements. Water concentrations were obtained almost exclusively from MEXT because some DOD installations obtained their water from Japanese water systems. Some consumption of water from off-installation sources was deemed reasonable for those installations that obtained their drinking water from underground sources. Section 2 contains the detailed discussions of the environmental measurements, and their analysis and use in dose calculations.

Scenarios of exposure describe the conditions under which individuals are exposed to radiation. These include understanding how long a person was exposed, where they were located (indoors or outdoors) when exposed, what they were doing (sitting, walking, heavy labor) when they were exposed, and other factors. Our analyses describe these scenarios and their parameters for groups called potentially exposed populations (PEPs). PEPs include active duty military, and DOD civilian and contractor employees performing routine duties and performing humanitarian relief activities. The individuals engaged in humanitarian relief activities are presumed to receive the highest exposures and therefore the highest doses. Doses for children of ages from birth to adulthood were determined for five age-specific PEP categories.

Recognizing that DOD-affiliated individuals were located throughout Japan, but concentrated at and near certain installations, the DARWG consolidated some 63 individual locations into 14 more broadly-based locations (called DARWG locations) so that a location-based dose estimate could be prepared for each one. This approach combined with the use of very conservative parameter estimates was intended to assure that the doses would be representative of the all individuals at a location, except for those who may have been assigned to humanitarian relief or emergency response activities that could have increased their potential for exposure. Section 3 of the report contains the detailed discussions of the development of the PEPs, and the construction of the 14 DARWG locations. Location-based doses were not assessed for J-Village because of the limited availability of environmental data, and because visits to J-Village involved specific missions lasting less than one full day by individuals who were provided personnel dosimeters.

Environmental data were analyzed extensively to understand their quality and appropriateness for use in dose calculations. External dose rates from MEXT were used to supplement DOD and DOE measurements. However, to account for differences in equipment and methods, the MEXT data were adjusted to be consistent with DOD/DOE measurements. Similarly, air concentrations for installations around Tokyo in an area known as the Kanto Plain were evaluated and were determined to have wide variability, again due mostly to differences in equipment and methods. Consequently, results with high quality, continuous sampling, and sophisticated analysis methods obtained at Yokota AB and IMS Takasaki were used for the four locations in the Kanto Plain. Section 5.2.2 discusses the details of these analyses.

Dose results are reported in Table 33 through Table 36 for the groups of children and adults that are greater than the doses for any of the other groups for which calculations were

performed. Table ES-1 provides an overall summary of the effective doses and the thyroid doses for children less than 17 years old and for adults. Dose results for all categories of shore-based individuals are available on the OTR Web Site (http://registry.csd.disa.mil/otr).

**Table ES-1. Range of estimated doses during Operation Tomodachi**

| **Group** | **Effective Dose (rem [mSv])** | **Thyroid Dose (rem [mSv])** |
|---|---|---|
| Children (<17 y) | 0.002 to 0.16 [0.02 to 1.6] | 0.008 to 2.7 [0.08 to 27] |
| Adults (≥17 y) | 0.002 to 0.12 [0.02 to 1.2] | 0.007 to 1.2 [0.07 to 12] |

For adults, performing humanitarian efforts, and children, the calculated effective doses for all locations range from about 0.01 to 0.2 rem (0.1 to 2 mSv), and the thyroid doses range from about 0.01 to 3 rem (0.1 to 30 mSv). Radiation doses tend to be higher in children than in adults exposed under the same conditions as expected primarily because children are more sensitive to ionizing radiation and children's thyroid glands tend to be smaller than adults—see discussion in Section 6.1 for details. These radiation doses are low and would not require any intervention under U.S. radiological protection guidance. Any estimate of the probability of adverse health effects based on the ranges of radiation doses calculated in this report should be approached with caution. At effective doses less than about 5 to 10 rem (50 to 100 mSv), "risks of health effects are either too small to be observed or are nonexistent" (HPS, 2010).

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# Section 1.

# Introduction

## 1.1 Overview

This report presents the results of radiation dose assessments for the Department of Defense (DOD) shore-based population of interest (POI) during the 60-day period from March 12, 2011 to May 11, 2011 following a 9.0 magnitude earthquake and resulting tsunami that damaged the Fukushima Daichi nuclear power station in Japan.

The dose assessment process involved the collection and review of external radiation exposure rate information and radionuclide concentration results in air, water, and soil that were collected by various agencies of the DOD, the Department of Energy (DOE), the Government of Japan (GOJ) and others. Data were either used as reported or estimated using sound techniques for periods of time for which data were not available or when data were judged unreliable. These results were combined with very conservative values of exposure parameters, such as breathing rate, water ingestion rate, uncertainties in dose coefficients for internal radionuclides, and others to produce doses that are considered to be higher than the dose received by any member of the POI. Assessments to produce credible estimates of the doses and their associated uncertainties are currently underway and are expected to support our view that these reported doses are greater than any individual's true dose. These reported doses are intended only to inform those who were in Japan during the time of the incident, but should not be used for compensation decisions or studies on the medical effects of ionizing radiation exposures.

This report provides the technical basis for doses that will be posted on the Operation Tomodachi Registry Web Site. These doses and information about the possible health effects from them will be accessible to all members of the POI, members of the medical community, and the public at large.

Assessments of doses for individuals who were afloat, who participated in aircraft operations, and who visited J-Village are being prepared as well as reports or documents to provide 1) doses for fetuses/embryos and nursing infants, 2) the doses for shore-based individuals from probabilistic analysis, 3) radiation monitoring by in-vivo scanning, and 4) implementing procedures and methods for the OTR. These reports will be completed by the end of 2012 and result in the following documents:

- Probabilistic Analysis of Radiation Doses for Shore-Based Individuals in Operation Tomodachi (DTRA-TR-12-002).
- Radiation Internal Monitoring by In Vivo Scanning in Operation Tomodachi (DTRA-TR-12-004).
- Radiation Doses for Embryo and Fetus, and Nursing Infants from Operation Tomodachi (DTRA-TR-12-017).
- Radiation Doses for Fleet, Air, and J-Village Individuals in Operation Tomodachi (DTRA-TR-12-041).

- Standard Methods (SM) and Standard Operating Procedures (SOPs) for Responding to Operation Tomodachi Individual Dose Assessments and Responding to VA Radiogenic Disease Compensation Claims (AIPH SM/SOP).

### 1.2 The Release

At 1446 Japan Standard Time[2] on March 11, 2011, a 9.0 magnitude earthquake, the largest ever recorded in Japan, occurred at a depth of approximately 19 miles, 80 miles east of Sendai and 231 miles northeast of Tokyo off the coast of Honshu Island (USGS, 2011). This earthquake resulted in the automatic shutdown of 11 nuclear power plants at four sites along the northeast coast of Japan (Onagawa 1, 2, and 3; Fukushima Daiichi 1, 2, and 3; Fukushima Daini 1, 2, 3, and 4; and Tokai 2).

On March 11, 2011, Fukushima Daiichi Nuclear Power Station (FDNPS) Units 1, 2, and 3 were in operation, and Units 4, 5, and 6 were shut down for routine refueling and maintenance activities; the Unit 4 reactor fuel was offloaded to the Unit 4 spent fuel pool. As a result of the earthquake, offsite power was lost to FDNPS. The emergency diesel generators started at all six units providing alternating current (AC) electrical power to critical systems at each unit.

Approximately 40 minutes following the earthquake and shutdown of the operating units, the first large tsunami wave inundated the FDNPS followed by multiple additional waves. The estimated height of the tsunami exceeded the site design protection from tsunamis by approximately 8 meters (27 feet). The tsunami resulted in extensive damage to site facilities and a complete loss of AC electrical power at Units 1 through 4 (INPO, 2011). Units 5 and 6 maintained power from a single Unit 6 diesel generator that escaped damage from the natural disaster events.

Despite the actions of the reactor operators following the earthquake and tsunami, cooling was lost to the fuel in the Unit 1 reactor after several hours, the Unit 2 reactor after about 71 hours, and the Unit 3 reactor after about 36 hours, resulting in damage to the nuclear fuel shortly after the loss of cooling. Without timely response from offsite assistance, which appears to have been hampered by the devastation in the area and other factors, each unit eventually lost the capability to further extend cooling of the reactor cores. The resultant heat build-up caused by station blackout (i.e., loss of all electrical power) and subsequent loss of core-cooling capabilities resulted in core meltdown for Units 1, 2 and 3. Pressure buildup in containment necessitated periodic venting operations (GOJ, 2011a). Further losses of containment occurred when built-up hydrogen gas exploded in Units 1 and 3. Overall, significant amounts of radioactivity were released from FDNPS Units 1, 2, and 3 into the atmosphere as gases and aerosols and into the ocean through contaminated seawater that had been used for cooling the units (INPO, 2011).

The following list of events highlights DOD’s response to this disaster.

On March 13, 2011, the media first reported possible radiation exposure to U.S. forces occurred when the USS Ronald Reagan carrier strike encountered a radioactive cloud released from FDNPS while enroute to assist in humanitarian assistance and disaster relief (HADR)

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operations for Japan. Reported contamination situations continued to occur as U.S. aircraft, vessels, and personnel deployed to assist the Government of Japan (GOJ) in HADR operations.

On March 14, 2011, eight CH-46E Sea Knight helicopters located at Atsugi Naval Air Facility (NAF) moved into the III Marine Expeditionary Forces Forward (MEF FWD) Command Element at Sendai Airfield. The Sendai Airfield is located 50 miles north of FDNPS and was the closest U.S. facility outside of the hot zone.

On March 16, 2011, MC-130H United States Air Force (USAF) Special Operations Command aircraft also arrived at Sendai Airfield.

On March 16, 2011, U.S. Forces, Pacific Command (USPACOM) released guidance on health protection requirements for radiation exposure, and established criteria for U.S. Forces, Japan (USFJ) for hot and warm zone entries (USPACOM, 2011a).

On March 16, 2011, first internal monitoring scans were performed on DOD personnel returning from Japan at Puget Sound Naval Shipyard.

On March 17, 2011, USPACOM initiated Operation Pacific Passage, providing voluntary military assisted departure of American citizens and designated foreign nationals (USPACOM, 2011b). In addition, Camp Fuji Marines (Task Force Fuji) assisted III MEF FWD in opening Sendai Airfield for heavy lift military aircraft.

On March 18, 2011, USPACOM published initial potassium iodide (KI) guidance for personnel protection against radioactive iodine inhalation/ingestion (USPACOM, 2011c).

On March 19, 2011, first Pacific Passage flight departed Yokota Air Base (AB).

On March 20, 2011, first C-17 landed at Sendai Airfield. U.S. Forces, Japan (USFJ) released supplemental Operation Tomodachi (OT) guidance, including potassium iodide (KI) and hot zones (USFJ, 2011a). Radioactive iodine was detected in the Tokyo water supply. Admiral (ADM) Willard, Commander, USPACOM, and ADM Walsh, USPACFLT arrive in Japan.

On March 23, 2011, U.S. Ambassador Roos, ADM Willard, ADM Walsh, and Lieutenant General (Lt Gen) Fields, Commander, USFJ traveled to Sendai Airfield.

On March 25, 2011, the GOJ extended its FDNPS evacuation zone from 20 km (12.4 miles) to 30 km (18.6 miles).

On March 26, 2011, The Commander, U.S. Pacific Fleet (COMPACFLT) issued medical and radiological limit guidance (COMPACFLT, 2011).

On March 27, 2011, last Operation Pacific Passage flight departed for United States.

On April 1, 2011, aircraft decontamination operation began at Atsugi NAF.

On April 1, 2011, USPACOM issued OT I-131 water activity standards as 100 Bq $L^{-1}$ for infants and pregnant/lactating mothers, and 300 Bq $L^{-1}$ for all others. The standards recommended bottled water for use if limits were exceeded.

On April 14, 2011, DOD personnel internal monitoring scan program was initiated in Japan.

On July 26, 2011, internal monitoring scans were made available to all members of the DOD-affiliated population.

On September 1, 2011, the internal monitoring scan program was completed.

Much of DOD's support to Japan was provided under HADR programs for international assistance. These programs involve a wide range of activities, and forms and levels of effort. In assessing radiation doses to the DOD-affiliated populations who worked directly in these support activities, this report uses the terms "humanitarian relief" to mean a specific set of exposure circumstances that characterize the parameters used in dose calculations. The report recognizes that these activities are at least partially performed within the scope of HADR programs, but will use the term "humanitarian relief" in discussing radiation exposures and doses to one specific category.

### 1.3 DOD's Presence in Japan

There are approximately 63 U.S. military facilities including major military bases located on the four main islands of Japan (Hokkaido, Honshu, Shikoku, and Kyushu). The Okinawa Prefecture, where approximately 50 percent of the U.S. military is stationed in Japan, is not considered a main island, because it consists of the Ryuku Island chain that stretches over 620 miles southwest from Kyushu to Taiwan. A dose assessment for the Okinawa Prefecture and other adjacent areas, e.g. Korea, was not performed for this report because DOD radiation sampling data demonstrated minimal radiation exposures to these areas/populations compared to exposure rates recorded for Honshu.

The potentially affected U.S. military facilities are concentrated in a few prefectures, 15 in Kanagawa, 10 in Nagasaki, and six in Tokyo. About 53,000 DOD-affiliated personnel (military, civilian, dependent) are located in these shore facilities. A breakout of affected shore-based personnel is shown in Table 1. DOD estimates about 17,000 individuals were afloat, participated in air crew operations or visited J-Village for a total of nearly 70,000 individuals in the DOD POI.

The main U.S. bases include Misawa AB in Aomori Prefecture, Yokota AB (Headquarters, USFJ) in Tokyo Prefecture, Yokosuka Naval Base (NB; aka U.S. Fleet Activities Yokosuka) and Atsugi NAF in Kanagawa Prefecture, Iwakuni Marine Corps Air Station (MCAS) near Hiroshima, and Sasebo NB (aka U.S. Fleet Activities Sasebo) in Nagasaki Prefecture.

As shown in Figure 1, Japan is divided into 47 sub-national jurisdictions known as prefectures. Japanese prefectures are analogous to U.S. states. For geographical location identification purposes, prefectures are tabulated by a sequential number with a preceding "P-".

This "P-##" numbering scheme is to minimize confusion with other numbering schemes used throughout this report. The prefecture numbering scheme starts at the most northernmost prefecture (Hokkaido), runs in the southerly direction, and finishes with the southernmost prefecture (Okinawa).

Table 1. Shore-based, DOD-affiliated population by location

| Prefecture No. | Location | No. of Military | No. of Civilians | No. of Dependents | Total People | DOD Family Housing |
|---|---|---|---|---|---|---|
| P-2 | Misawa AB | 3,749 | 227 | 4,392 | 8,368 | Yes |
| P-13 | Yokota AB | 2,879 | 594 | 4,434 | 7,907 | Yes |
| P-13 | Akasaka Press Center | 8 | 9 | 8 | 25 | No |
| P-14 | Atsugi NAF | 3,001 | 142 | 2,715 | 5,858 | Yes |
| P-14 | Yokosuka NB | 7,815 | 556 | 4,833 | 13,204 | Yes |
| P-14 | Negishi Housing | 433 | 152 | 619 | 1,204 | Yes |
| P-14 | Ikego Housing | 510 | 200 | 1,324 | 2,034 | Yes |
| P-14 | Sagami General Depot | 8 | 41 | 57 | 106 | Yes |
| P-14 | Sagamihara Housing | 267 | 130 | 871 | 1,268 | Yes |
| P-14 | Camp Zama | 469 | 427 | 911 | 1,807 | Yes |
| P-14 | Yokohama North Dock | 2 | 3 | 2 | 7 | No |
| P-22 | Camp Fuji | 142 | 6 | 12 | 160 | No |
| P-34 | Kawakami Ammunition Depot | 0 | 3 | 1 | 4 | No |
| P-34 | Kure Pier No.6 | 30 | 8 | 15 | 53 | Yes |
| P-35 | Iwakuni MCAS | 2,853 | 348 | 2,144 | 5,345 | Yes |
| P-42 | Sasebo NB | 3,202 | 224 | 1,344 | 4,770 | Yes |
| P-42 | Hario Housing | 297 | 42 | 847 | 1,186 | Yes |
| | Total: | 25,665 | 3,112 | 24,529 | 53,306 | - |

Information in this table obtained from USG ( 2011)

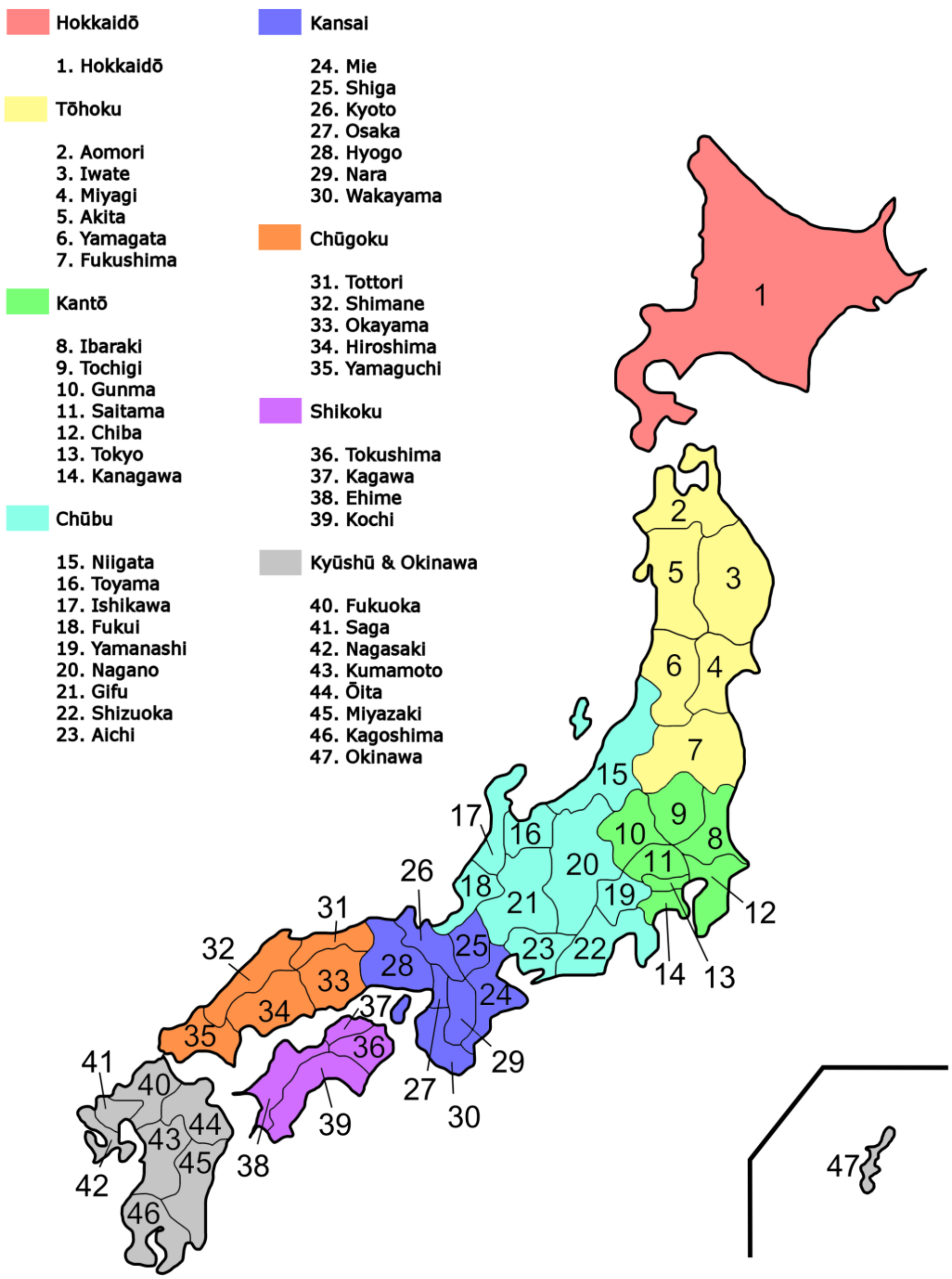


**Figure 1. Map of Japan's prefectures**

In addition to the major U.S. bases, there are associated housing areas, and numerous smaller U.S. work locations. Some of these include petroleum, oil, and lubricant (POL) depots, ammunition depots, communication sites, naval locations, and various storage and training areas.

During the 60-day period of interest, U.S. shore forces were also co-located with Japanese military at Japanese self-defense force locations (e.g. Hyakuri AB) or Japanese cities in humanitarian support roles (e.g. City of Ishinomaki). A listing of these 63 locations is shown in Table 2. A location numbering scheme is introduced for tabulation purposes. Locations are tabulated by a sequential number with a preceding “L-”.

A third and final numbering scheme is also introduced in Table 2—the DARWG location. The purpose of the number will be explained in Section 2, but for now it is sufficient to note that it is a sequential number (1–14), preceded by “D-”.

Table 2 lists 63 shore locations where DOD-affiliated individuals may have been located, two reference locations (FDNPS and International Monitoring System (IMS), Takasaki) and their associated decimal degree longitude and latitude coordinates. This geographical coordinate tabulation provides the basis for a distance determination between FDNPS and the potentially affected shore location. Distance calculations were performed in MS Excel using decimal latitude/longitude (six or seven significant figures) using the popular great circle formulation (Pearson, 2011).

These distance calculations illustrate that all permanent U.S. facilities (including all dependents in DOD family housing) were located in excess of 100 miles from the FDNPS—see Figure 2. The closest temporary location to FDNPS was J-Village (a soccer training center) at 12 miles. All U.S. personnel visiting this site were issued external radiation dosimeters and afforded the opportunity for internal monitoring. The next closest site was Sendai Airport at 50 miles.

**Table 2. Shore locations**

| Location No. | Shore Location | Prefecture No. | City, Prefecture | DARWG No. | DARWG Location | Latitude | Longitude | Dist. From FDNPS (miles) |
|---|---|---|---|---|---|---|---|---|
| L-1 | Hachinohe POL Depot | P-2 | Hachinohe, Aomori | D-1 | Misawa AB | 40.50 | 141.48 | 214 |
| **L-2** | **Misawa Air Base** | **P-2** | **Misawa, Aomori** | **D-1** | **Misawa AB** | **40.71** | **141.37** | **228** |
| L-3 | Misawa ATG Range (Ripsaw Range) | P-2 | Misawa, Aomori | D-1 | Misawa AB | 40.71 | 141.37 | 228 |
| L-4 | Shariki Communication Site | P-2 | Tsugaru, Aomori | D-1 | Misawa AB | 40.80 | 140.38 | 236 |
| L-5 | City of Ofunato | P-3 | Ofunato, Iwate | D-2 | Sendai | 39.07 | 141.72 | 120 |
| L-6 | Camp Sendai | P-4 | Sendai, Miyagi | D-2 | Sendai | 38.27 | 140.92 | 59 |
| **L-7** | **Sendai Airport** | **P-4** | **Sendai, Miyagi** | **D-2** | **Sendai** | **38.14** | **140.92** | **50** |
| **L-8** | **City of Ishinomaki** | **P-4** | **Ishinomaki, Miyagi** | **D-3** | **Ishinomai** | **38.43** | **141.32** | **72** |
| L-9 | Matsushima Air Base (JSDF) | P-4 | Ishinomaki, Miyagi | D-3 | Ishinomaki | 38.38 | 141.07 | 66 |
| **L-10** | **City of Yamagata** | **P-6** | **Yamagata, Yamagata** | **D-4** | **Yamagata** | **38.26** | **140.34** | **69** |
| **L-11** | **J-Village (Fukushima Staging Area)** | **P-7** | **Hama-dori, Fukushima** | **D-5** | **J-Village** | **37.25** | **141.00** | **12** |
| L-12 | Chosi Port | P-12 | Chosi, Chiba | D-6 | Hyakuri | 35.73 | 140.83 | 117 |
| L-13 | Narita | P-12 | Narita, Chiba | D-6 | Hyakuri | 35.78 | 140.32 | 120 |
| **L-14** | **Hyakuri Air Base** | **P-8** | **Omitama, Ibaraki** | **D-6** | **Hyakuri** | **36.18** | **140.42** | **92** |
| L-15 | City of Ishioka | P-8 | Ishioka, Ibaraki | D-6 | Hyakuri | 36.19 | 140.29 | 95 |

**Table 2. Shore locations (cont.)**

| Location No. | Shore Location | Prefecture No. | City, Prefecture | DARWG No. | DARWG Location | Latitude | Longitude | Dist. From FDNPS (miles) |
|---|---|---|---|---|---|---|---|---|
| L-16 | City of Mito | P-8 | Mito, Ibaraki | D-6 | Hyakuri | 36.37 | 140.47 | 79 |
| L-17 | City of Tsukuba | P-8 | Tsukuba, Ibaraki | D-6 | Hyakuri | 36.08 | 140.08 | 107 |
| **L-18** | **City of Oyama** | **P-9** | **Oyama, Tochigi** | **D-7** | **Oyama** | **36.31** | **139.80** | **102** |
| L-19 | Camp Asaka (AFN Transmitter Site) | P-11 | Wako, Saitama | D-8 | Yokota AB | 35.80 | 139.59 | 138 |
| L-20 | Owada Communication Site | P-11 | Niiza, Saitama | D-8 | Yokota AB | 35.80 | 139.57 | 138 |
| L-21 | Tokorozawa Communications Station | P-11 | Tokorozawa, Saitama | D-8 | Yokota AB | 35.80 | 139.47 | 142 |
| **L-22** | **Yokota Air Base** | **P-13** | **Fussa, Tokyo** | **D-8** | **Yokota AB** | **35.75** | **139.35** | **149** |
| L-23 | Fuchu Communications Station | P-13 | Fuchu, Tokyo | D-8 | Yokota AB | 35.67 | 139.48 | 149 |
| L-24 | Tama Service Annex | P-13 | Inagi, Tokyo | D-8 | Yokota AB | 35.64 | 139.45 | 152 |
| L-25 | Yugi Communication Site | P-13 | Hachioji, Tokyo | D-8 | Yokota AB | 35.64 | 139.35 | 155 |
| L-26 | Fukaya Communication Site | P-14 | Yokohama, Kanagawa | D-8 | Yokota AB | 35.68 | 139.48 | 148 |
| **L-27** | **Akasaka Press Center (Hardy Barracks)** | **P-13** | **Minato, Tokyo** | **D-9** | **Toyko** | **35.66** | **139.73** | **142** |
| L-28 | New Sanno U.S. Forces Center | P-13 | Minato, Tokyo | D-9 | Toyko | 35.65 | 139.72 | 143 |
| L-29 | U.S. Embassy | P-13 | Akasaka Minato-ku, Tokyo | D-9 | Toyko | 35.67 | 139.74 | 141 |

**Table 2. Shore locations (cont.)**

| Location No. | Shore Location | Prefecture No. | City, Prefecture | DARWG No. | DARWG Location | Latitude | Longitude | Dist. From FDNPS (miles) |
|---|---|---|---|---|---|---|---|---|
| L-30 | Camp Zama | P-14 | Zama, Kanagawa | D-10 | Atsugi NAF | 35.51 | 139.39 | 160 |
| **L-31** | **Naval Air Facility Atsugi** | **P-14** | **Ayase, Kanagawa** | **D-10** | **Atsugi NAF** | **35.45** | **139.45** | **162** |
| L-32 | Naval Support Facility Kamiseya | P-14 | Ayase, Kanagawa | D-10 | Atsugi NAF | 35.49 | 139.49 | 159 |
| L-33 | Sagami General Depot | P-14 | Sagamihara, Kanagawa | D-10 | Atsugi NAF | 35.58 | 139.38 | 157 |
| L-34 | Sagamihara Housing Area | P-14 | Sagamihara, Kanagawa | D-10 | Atsugi NAF | 35.52 | 139.42 | 159 |
| L-35 | Azuma Storage Area | P-14 | Yokosuka, Kanagawa | D-11 | Yokosuka NB | 35.41 | 139.64 | 159 |
| L-36 | Ikego Housing Area and Navy Annex | P-14 | Zushi, Kanagawa | D-11 | Yokosuka NB | 35.31 | 139.59 | 167 |
| L-37 | Naval Transmitter Station Totsuka | P-14 | Yokohama, Kanagawa | D-11 | Yokosuka NB | 35.42 | 139.64 | 158 |
| L-38 | Negishi Dependent Housing Area | P-14 | Yokohama, Kanagawa | D-11 | Yokosuka NB | 35.42 | 139.64 | 158 |
| L-39 | Tomioka Storage Area | P-14 | Yokohama, Kanagawa | D-11 | Yokosuka NB | 35.42 | 139.64 | 158 |
| L-40 | Tsurumi POL Depot | P-14 | Yokohama, Kanagawa | D-11 | Yokosuka NB | 35.49 | 139.71 | 152 |
| **L-41** | **United States Fleet Activities Yokosuka** | **P-14** | **Yokosuka, Kanagawa** | **D-11** | **Yokosuka NB** | **35.29** | **139.67** | **165** |
| L-42 | Urago Ammunition Depot | P-14 | Yokosuka, Kanagawa | D-11 | Yokosuka NB | 35.30 | 139.65 | 166 |
| L-43 | Yokohama North Dock | P-14 | Yokohama, Kanagawa | D-11 | Yokosuka NB | 35.47 | 139.64 | 155 |

**Table 2. Shore locations (cont.)**

| Location No. | Shore Location | Prefecture No. | City, Prefecture | DARWG No. | DARWG Location | Latitude | Longitude | Dist. From FDNPS (miles) |
|---|---|---|---|---|---|---|---|---|
| L-44 | Kisarazu Auxiliary Landing Field | P-12 | Kisarazu, Chiba | D-11 | Yokosuka NB | 35.40 | 139.91 | 153 |
| **L-45** | **Camp Fuji** | **P-22** | **Gotenba, Shizuoka** | **D-12** | **Camp Fuji** | **35.32** | **138.87** | **189** |
| L-46 | Numazu Training Area | P-22 | Numazu, Shizuoka | D-12 | Camp Fuji | 35.10 | 138.87 | 201 |
| L-47 | Akizuki Ammunition Depot | P-34 | Etajima, Hiroshima | D-13 | Iwakuni MCAS | 34.22 | 132.45 | 529 |
| L-48 | Haigamine Communication Site | P-34 | Kure, Hiroshima | D-13 | Iwakuni MCAS | 34.25 | 132.57 | 522 |
| L-49 | Hiro Ammunition Depot | P-34 | Kure, Hiroshima | D-13 | Iwakuni MCAS | 34.25 | 132.57 | 522 |
| L-50 | Kawakami Ammunition Depot | P-34 | Higashi-hiroshima, Hiroshima | D-13 | Iwakuni MCAS | 34.42 | 132.73 | 509 |
| L-51 | Kure Pier No. 6 | P-34 | Kure, Hiroshima | D-13 | Iwakuni MCAS | 34.25 | 132.57 | 522 |
| **L-52** | **Iwakuni Marine Corps Air Station** | **P-35** | **Iwakuni, Yamaguchi** | **D-13** | **Iwakuni MCAS** | **34.15** | **132.24** | **542** |
| L-53 | Sofu Communication Site | P-35 | Iwakuni, Yamaguchi | D-13 | Iwakuni MCAS | 34.15 | 132.24 | 542 |
| L-54 | Akasaki POL Depot | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| L-55 | Hario Dependent Housing Area | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| L-56 | Harioshima Ammunition Storage Area | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |

**Table 2. Shore locations (cont.)**

| Location No. | Shore Location | Prefecture No. | City, Prefecture | DARWG No. | DARWG Location | Latitude | Longitude | Dist. From FDNPS (miles) |
|---|---|---|---|---|---|---|---|---|
| L-57 | Iorizaki POL Depot | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| L-58 | Sakibe Navy Annex | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| L-59 | Sasebo Ammunition Supply Point | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| L-60 | Sasebo Dry Dock Area | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| L-61 | Tategami Basin Port Area | P-42 | Sasebo, Nagasaki | D-14 | Sasebo NB | 33.16 | 129.71 | 703 |
| **L-62** | **United States Fleet Activities Sasebo** | **P-42** | **Sasebo, Nagasaki** | **D-14** | **Sasebo NB** | **33.16** | **129.71** | **703** |
| L-63 | Yokose POL Depot | P-42 | Saikai, Nagasaki | D-14 | Sasebo NB | 32.93 | 129.65 | 713 |
| N/A | Fukushima-Daiichi Nuc. Pwr. Sta. (FDNPS) | P-7 | | N/A | N/A | 37.42 | 141.03 | 0 |
| N/A | International Monitoring Site (IMS) Takasaki | P-10 | | N/A | N/A | 36.30 | 139.08 | 133 |

Ref: (USFJ, 2011b; USG, 2011; Wikipedia, 2011)


**Figure 2. Map of major U.S. military bases (red stars) and FDNPS (yellow trefoil)**

## 1.4 Tasking

Four days post-earthquake and tsunami, the Chairman, Senate Veterans' Affairs Committee (SVAC) contacted the Secretary of Defense and expressed concerns about U.S. forces providing disaster response in Japan that might be exposed to radiation and other environmental toxins (SVAC, 2011). The SVAC Chairman urged DOD to create a database of U.S. Service members supporting the relief effort in Japan to track data related to exposure to radiation and other environmental toxins. The Under Secretary of Defense for Personnel and Readiness (USD(P&R)) responded that DOD was working with the Department of Veterans Affairs (VA) to ensure that affected Service members were being appropriately monitored for environmental exposures and that the defense department would create comprehensive databases to include all affected Service members, family members, and DOD civilian employees and contractors (USD(P&R), 2011).

After determining the appropriate DOD offices to complete this work, the Assistant Secretary of Defense for Health Affairs (ASD(HA)) requested that the Army Institute of Public Health (AIPH) serve as the lead organization for the creation and operation of the Operation Tomodachi Registry (OTR) (ASD(HA), 2011a). Planning, development, and implementation activities required to establish the OTR were delegated to an OT Steering Committee and four working groups: the OTR Implementation Working Group (OTRIWG), the Dose Assessment

and Recording Working Group (DARWG), the Population of Interest Working Group (POIWG), and the Medical and Claims Users Working Group (M&CUWG). Briefly, the primary focus and scope of each working group include:

- OTRIWG: develop an approach to construct and sustain the OTR in a manner that will withstand scrutiny from the various stakeholders and Congress.
- DARWG: conduct dose assessments using all relevant data of sufficient data quality.
- POIWG: Collect and organize once-daily personnel location data for all DOD affiliated personnel associated with Operation Tomodachi.
- M&CUWG: Define OTR data needed to support claims adjudication, medical surveillance, and general health-related inquiries.

The ASD(HA), as the DOD office responsible for establishing the OTR requested the Director, Armed Forces Radiobiology Research Institute (AFRRI) establish the Dose Assessment and Recording Working Group (DARWG) with technical and acquisition support provided by the Defense Threat Reduction Agency (DTRA) Nuclear Test Personnel Review Program (ASD(HA), 2011b). The U.S. Army (USA), U.S. Navy (USN), and U.S. Air Force (USAF) were also requested to provide one knowledgeable, trained health physicist to support the DARWG.

This report provides the technical basis for doses that are currently available on the OTR web site (http://registry.csd.disa.mil/otr), and is being posted to the OTR website as well.

### 1.5 Scope of this Report

The purpose of this report is to discuss the approach, methods, and results of an initial study to estimate conservative radiation doses that may be assigned to individuals who are part of a potentially exposed population (PEP). Radiation doses from releases of radioactive material from the FDNPS accident are calculated based on an assumed exposure period of 60 days from March 12, 2011 to May 11, 2011. This 60-day period is based on a previous DARWG analysis (DARWG, 2011a) and is discussed in Section 3.4.

All members of the DOD-affiliated population (Service members, civilian employees, family members of Service members and civilian employees, and contractor employees) and their dependents, (referred to as DOD-affiliated individuals) will be assigned to a PEP. The OTR Steering Group recognized that doses that are calculated using parameter values that could be considered “worst case” do not represent the daily activities of most persons in the POI and could lead to unnecessary concerns about potential health effects. To mitigate these concerns, the steering group requested the calculation of doses under representative conditions of daily physical activity and accounting for the protective features of time spent indoors.

This report represents the start of a process to assess radiation doses and, eventually, potential health risks. According to the National Council on Radiation Protection and Measurements (NCRP) in *Radiation Dose Reconstruction: Principles and Practices*, “It is necessary to view dose reconstruction as a *process* that begins with a defined purpose and is carried out in a logical and orderly manner.” (NCRP, 2009a) The National Academy of Sciences (NAS, 1995) recommended that preliminary or scoping studies using realistic assumptions about

potential radiation doses, the population size, and expected adverse health effects, precede comprehensive dose reconstruction efforts. A scoping study will also help to further define potentially exposed populations and ranges of potential radiation doses (NAS, 1995). The DARWG recommended and the OTR Steering Group concurred that to best meet the tasking requirements (see Section 1.4) the DARWG would create a report estimating radiation doses to DOD-affiliated personnel using conservative estimates of the relevant parameters rather than pursuing realistic estimates. A study is currently underway to produce realistic radiation dose estimates and their associated uncertainties using probabilistic methods that use realistic distributions of the important parameters for calculations of dose. DARWG anticipates the report of this effort, peer-reviewed by the NCRP will be available in late 2012 and posted on the OTR Web Site.

Following a nuclear reactor accident, the potential exists for radioactive materials to be released from the core of the reactor and into the environment. Among the radioactive materials that might be released, radioactive iodine, cesium, tellurium and noble gases comprise the major contributors to radioactivity. If ingested or inhaled by individuals these materials are distributed throughout the body and may be preferentially absorbed and retained by specific organs and tissues.

Cesium distributes generally throughout the body and is not concentrated in any particular organ or tissue. However, radioactive iodine that is inhaled or ingested is preferentially absorbed and concentrated in the thyroid gland. Because of this concentration of radioactive iodine and the radiation dose it produces, the thyroid gland is the principal organ of concern for health effects.

This report does not address regulatory issues or the traditional areas of radiation safety or protection, that is, the control of radiation hazards based on elimination of the radiation source, substitution with a different method, engineering and administrative controls on radiation sources or personnel, and the use of personal protective equipment. Additionally, the report does not take into account any personal actions that might have reduced doses such as administration of KI, use of personal protective equipment, or implementation of procedures to maintain radiation doses as low as reasonably achievable (ALARA) that are matters of U.S. regulatory guidance for radiological incidents and accidents.[3] Rather, the report addresses concerns arising from the accidental release of radioactive material, the ensuing emergency response and recovery actions, and their associated radiation doses to which standard radiation protection guidance does not apply.

## 1.6 Radiological Terms

In this report, radiological quantities are expressed using either the International System of Units (SI) or traditional units. Measurement results are expressed in the units reported in source documents. DOD more commonly uses traditional units for reporting doses; therefore, for this report, the doses are reported in units or subunits of rem with the SI equivalent value in millisievert (mSv) in parentheses.

[3] For example, the U.S. FDA recommends the administration of potassium iodide for the protection of the thyroid when the predicted thyroid dose is 5 rad (50 mGy) or more for children (<17 years old) and pregnant or lactating women (FDA, 2001).

Table 3 presents the radiation dose terms used in the report, their definitions, and clarifying comments.

To describe the radiation dose from intakes of radioactive material (internal radiation dose), the radiation protection community uses “committed doses” of various types (see Table 3). Committed dose is a radiation protection quantity and means that the radiation doses from intakes of radioactive materials are calculated based on the behavior of the radioactive material in a reference person for a period of 50 years (adults) after an intake or until age 70 (children). Although the radiation doses from internal radioactive materials are actually delivered over time after an intake, this total committed dose is recorded as if it was all received at the time the intake occurred.

The calculations for radiation dose from internal radioactive materials in this report are based on dose coefficients (DCs) derived from recommendations published in ICRP Publication 60 (ICRP, 1991) and used in the ICRP databases of DCs (ICRP, 2001, 2003, and 2007b).

**Table 3. Radiation dose terms**

| Radiation Dose Term | Symbol and Definition | Comments |
|---|---|---|
| Activity | A | The mean number of spontaneous nuclear transformations occurring in an amount of radionuclide in a particular energy state in a given time interval. The unit for activity in the SI system is reciprocal second ($s^{-1}$) (i.e., one nuclear transformation per second), with the special name becquerel (Bq). The special unit previously used was curie (Ci); 1 Ci = $3.7 \times 10^{10}$ Bq. (NCRP, 2009a) |
| Absorbed (Organ) Dose | $D_T$ | As used in this report, the absorbed dose is the amount of energy deposited in an organ or tissue divided by the mass of the organ or tissue. The SI unit for organ dose is J $kg^{-1}$ and is given the special name gray (Gy). The conventional unit for absorbed dose used in the U.S. is the rad; 1 rad = 0.01 Gy. |
| Radiation Weighting Factor | $w_R$ | The radiation weighting factor is a unitless, multiplicative factor applied to the absorbed dose to account for probability of the type and energy of the radiation to cause stochastic effects (e.g., cancer). |
| Equivalent Dose | $\mathrm{H_T} = \sum_{\mathrm{R}} \mathrm{w_R D_{T,R}}$ | The equivalent dose to a tissue or organ, T, from radiation, R, is the absorbed dose multiplied by the radiation weighting factor. The radiation weighting factor is unitless; therefore the units of equivalent dose are the same as for absorbed dose, J $kg^{-1}$. The special name for the SI unit of equivalent dose is the sievert (Sv). The conventional unit for equivalent dose used in the U.S. is the rem; 1 rem = 0.01 Sv. |
| Tissue Weighting Factor | $w_T$ | The tissue weighting factor for a particular organ or tissue is used to account for the "relative contribution of that organ or tissue to the total detriment [*e.g*, cancer] due to these effects resulting from a uniform irradiation of the whole body." (ICRP, 1991) The values for $w_T$ are based on a "reference population of equal numbers of both sexes and a wide range of ages." (ICRP, 1991) The values are independent of radiation type and energy and apply to workers and the general population of both sexes (ICRP, 1991).<br>The sum of the tissue weighting factors is one to ensure "that a uniform equivalent dose over the whole body should give an effective dose [See next entry.] numerically equal to that uniform equivalent dose" (ICRP, 1991). |

**Table 3. Radiation dose terms (cont.)**

| Radiation Dose Term | Symbol and Definition | Comments |
|---|---|---|
| Effective Dose | $E = \sum_{T} w_T H_T$ <br> or <br> $E = \sum_{T} w_T \sum_{R} w_R D_{T,R}$ <br> $= \sum_{T} w_T \sum_{R} H_{T,R}$ | The effective dose is the sum of the tissue weighted equivalent doses to all the tissues and organs as presented in ICRP Publication 60 (ICRP, 1991) and used in the ICRP (2001, 2003, and 2007b) databases of DCs. The special name for the SI unit, J $kg^{-1}$, of effective dose is the sievert (Sv). The conventional unit for effective dose used in the U.S. is the rem; 1 rem = 0.01 Sv. <br> Alternately, the effective dose is the doubly weighted sum (radiation and tissue weighting factors) of the absorbed organ doses. |
| Committed Equivalent Dose | $H_{T,\tau}$ or $H_T(\tau)$ | The committed equivalent dose is the equivalent dose to a tissue or organ from internally deposited radionuclides during the period τ following an intake. For workers a period of 50 years is used; for members of the public the period is 50 years and for children the period is from exposure to age 70. |
| Total Thyroid Equivalent Dose | $H_{Thy}$ | The total thyroid equivalent dose is equal to the sum of external radiation dose (equivalent dose to the whole body) and internal radiation dose (committed equivalent dose to the thyroid). In this report, the total thyroid equivalent dose is called the thyroid dose. |
| Committed Effective Dose | $E(\tau)$ | The committed effective dose is the effective dose from internally deposited radionuclides during the period τ following an intake. For workers a period of 50 years is used; for members of the public the period is 50 years and for children the period is from exposure to age 70. |
| Total Effective Dose | TED | The TED is used most often to demonstrate compliance with standards. The TED is calculated by summing the external radiation dose (e.g., E) and the committed effective dose. In this report, the TED is called the whole body effective dose. |

For radiation doses from sources outside the body (external radiation dose) in the absence of internal radiation dose, the external radiation dose is equivalent to a quantity called effective dose. This equivalency and the definition of effective dose are shown in Table 3. In practice, the external radiation dose is estimated from personal radiation monitors (dosimeters), by measurements of the external radiation field (surveys), or from knowledge of the radiation sources in the area. It is usually assumed that the whole body received a uniform radiation dose as determined from dosimeters, surveys, or calculations.

## 1.7 Overview of the Dose Assessment

The quantities calculated in this report are whole body effective dose and thyroid dose as presented in ICRP Publication 60 (ICRP, 1991) and used in the ICRP databases of DCs (ICRP, 2001, 2003, and 2007b). The effective dose replaced the quantity “effective dose equivalent” (EDE)[4] in the 1990 recommendations of the ICRP (1991). In its 1990 recommendations with the introduction of the effective dose, the ICRP did not recommend attempts to change earlier values of the EDE to effective doses. In addition, the Commission stated that values of the effective dose equivalent can be added to values of effective doses “without any adjustment” (ICRP, 1991). The effective dose and equivalent dose “provide a basis for estimating the probability of stochastic effects only for doses well below the threshold for deterministic effects” and “are intended for use in radiation protection, including the assessment of risk in general terms” (ICRP, 1991).

DARWG considers the doses in this report to be conservative estimates that can be expected to be greater than the dose any individual actually receives. DARWG expects that these doses will be shown to be greater than the doses received by 95 of 100 exposed individuals based on the best estimates of dose and associated uncertainties resulting from probabilistic dose assessment that are in progress (Chehata et al., 2012). To estimate these radiation doses, the DARWG assumes that (1) the potentially exposed populations are exposed to the radiological conditions described by the environmental data presented in Section 2 of this report, (2) the human behavior or habit data are “upper percentile” values (EPA, 2011) including accounting for time spent indoors and different physical activity levels, and (3) the inhalation and ingestion dose coefficients from ICRP databases released on compact disc read-only memory (CD-ROM) (ICRP, 2001, 2003, and 2007b) apply assuming 1 µm activity median aerodynamic diameter (AMAD) aerosols. The results of internal monitoring are compared with the doses as an independent evaluation of the doses to internal organ.

The dose assessment in this report is based on measured environmental data: external photon radiation dose rates and measured activity concentrations of radioactive materials in air, water, and soil. Where environmental measurement data were lacking several approaches were used, for example:

- Cesium-137 was used as a reference radionuclide to infer concentrations of radioactive material not measured; e.g., an average Te-129m to Cs-137 ratio determined from measurements made at Yokota AB was used to calculate the Te-129m air concentration at Yokosuka NB based on measured Cs-137 air concentrations;

[4] The U.S. Government still uses the term EDE in its regulations.

- External radiation measurements from GOJ or Department of Energy (DOE) resources near DOD facilities were used where there were no DOD external radiation measurements; and,
- Linear interpolations were used between measured external radiation dose rates to estimate external radiation dose rates at those times when there were no measurements.

The basic exposure model used is to assume that a hypothetical person representative of a much larger population:

- Is exposed to photons[5] from a passing plume and external deposits of radioactive material;
- Breathes contaminated air from the passing plume(s) and resuspended material;
- Ingests radioactive material in water, soil, and dust each day; and,
- Ingests negligible amounts of radioactive material from food.

An hourly whole body effective dose and an hourly thyroid dose were computed for each of the components above and summed over the 60-day period from March 12 through May 11, 2011. These doses are produced during exposure to both external and internal radiation sources. The DARWG believes that the whole body effective doses and thyroid doses are conservative indicators of potential health effects for the DOD-affiliated population of concern.

[5] Photons are the radiation type typically responsible for external exposures and commonly include x rays and gamma rays.

# Section 2.

# Environmental Monitoring

## 2.1 Overview

The response to the FDNPS radiological accident included environmental measurements to characterize the radiological release from the plant, to describe the environmental transport of the radiological constituents, and to assess potential impacts to health. Some of the environmental sampling conducted during the response continued the routine radiological sampling that was being conducted in Japan before the accident, while other sampling was specifically implemented in response to the accident. The results of environmental sampling used in this dose reconstruction effort were from all four DOD military services, DOE teams, and Japanese sources (Tokyo Electric and Power Company [TEPCO] and the Ministry of Education, Culture, Sports, Science, and Technology [MEXT]). This order of precedence (DOD, DOE, Japanese sources) recognizes that DOD data were collected on DOD installations or where DOD personnel were deployed. Some DOE data were also collected under those same conditions. Although Japanese data were not collected at DOD locations, they were valuable in filling data gaps when DOD and DOE data were not available, and when used for corroboration of DOD and DOE data.

Environmental data described in detail in this section were the primary data used to calculate doses for this report. Environmental sampling was conducted for a number of purposes. The most important reason for sampling was to assess the immediate potential for radiation exposures to members of the public at specific locations to determine acceptability for occupancy and whether special protective measures were warranted, for example in limiting consumption of water from environmental sources with known contamination. Sampling was conducted to determine the suitability of land areas for re-habitation post evacuation or future agricultural uses. Some data were not directly used to assess doses to individuals but supplemented other data. For example, the relationships among the concentrations of radionuclides evaluated in soil samples provided supporting information for air samples whose detection sensitivity may not have been sufficient for some isotopes or, in the case of bioassay measurements of individuals, where individual isotopes were not evaluated.

## 2.2 Sources of Radiation Exposure

Loss of cooling and other damage at the FDNPS following the earthquake and tsunami produced various types of damage to reactor structures and resulted in the ultimate release of radioactive materials to the environment. At FDNPS, the major source of radioactive materials that were dispersed beyond the site boundary resulted from irradiated reactor fuel that failed or melted and released fission products and other radionuclides for transport in air or water media. In its first report to the International Atomic Energy Agency (IAEA), the GOJ estimated releases of I-131 and Cs-137 of $1.5 \times 10^{17}$ Bq and $1.2 \times 10^{16}$ Bq during the period March 11 to April 5, 2011 (GOJ, 2011a). The irradiated fuel of concern is limited to fuel in the cores of FDNPS Units 1, 2 and 3. Units 5 and 6 were able to maintain sufficient backup power to core cooling systems to avoid core damage and achieved stable cold shutdown by March 20, 2011. The Unit 4 core

was empty. (GOJ, 2011a) The GOJ's second report to the IAEA with updated information about the FDNPS disaster provided a solid basis for ruling out any release of radioactive material from Spent Fuel Pools (SFP) in Units 1, 2, 5, and 6, as well as the site common SFP and the dry cask fuel storage facility (GOJ, 2011b).

Deliberate release of contaminated water ($\sim 1.5 \times 10^{11}$ Bq) at the FDNPS site, as well as leakage of highly contaminated water originating from Units 2 and 3 ($\sim 4.7 \times 10^{15}$ Bq and $\sim 2.0 \times 10^{13}$ Bq, respectively), also resulted in transfer of radioactive materials offsite. These releases to the sea were dominated by radioactive isotopes of cesium and iodine (GOJ, 2011a). The contaminated water source term for radioactive material released to the sea is not considered in this report because foodstuffs were monitored and consumption of fish was limited because of the damage from the earthquake and tsunami to the Japan's fishing industry (Johnson, 2011).

The measured radiation dose rates at the main gate of FDNPS over the period of interest shown in Figure 3 illustrate the sequence of airborne releases associated with the accident. For time periods lacking reported values at the Main Gate, measured values were obtained from nearby locations, e.g., West Gate and adjusted to be consistent with measurements at the Main Gate. Measurements of radioactive isotopes in air and soil indicated radionuclides at distances from the FDNPS over time. Those detections included the following:

- The noble gas Xe-133 was detected at the International Monitoring Station (IMS), Takasaki (Gunma Prefecture, ~ 130 miles WSW of FDNPS) during the period March 15 to March 29, 2011 and saturated the detector on March 15 while showing concentrations exceeding one kilobecquerel per cubic meter. Xe-133 concentrations decreased into the measureable range late on March 16 and tapered off, with intermediate activity concentration spikes on March 20 and 21 (CTBTO, 2011).
- Radioactive isotopes of iodine (I-131 and I-132), cesium (Cs-134, Cs-136, and Cs-137), and tellurium (Te-132) were detected on March 12 indicating release of volatile radioactive materials from Unit 1. Thereafter, detection of these isotopes and Te-129 and Te-129m coincided with the timing of peaks indicated in Figure 3 and Figure 4 and further shown in GOJ (2011b).
- Ba-140 was detected in soil samples in Fukushima Prefecture, and Sr-89 and Sr-90 were measured on site at the FDNPS and in Fukushima Prefecture (GOJ, 2011a; GOJ, 2011b).
- Mo-99, Tc-99m, La-140, and Nb-95 have been detected in aerosols and / or soil in several prefectures (GOJ, 2011a). Sampling and specific analyses for the actinides Pu-238, Pu-239, Pu-240, Am-241, Cm-242, and Cm-244 resulted in their detection within short distances of the site boundaries of the FDNPS (GOJ, 2011a; GOJ 2011b).

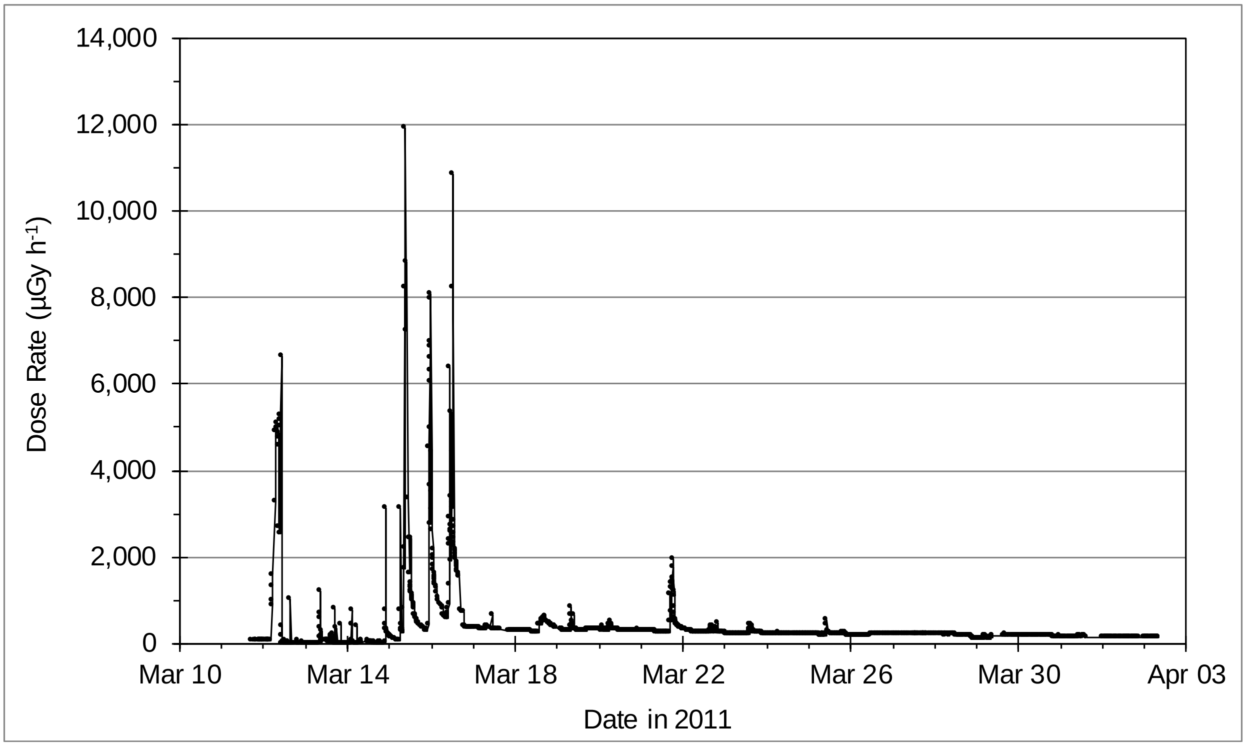


**Figure 3. TEPCO dose rate measurements for the FDNPS main gate**

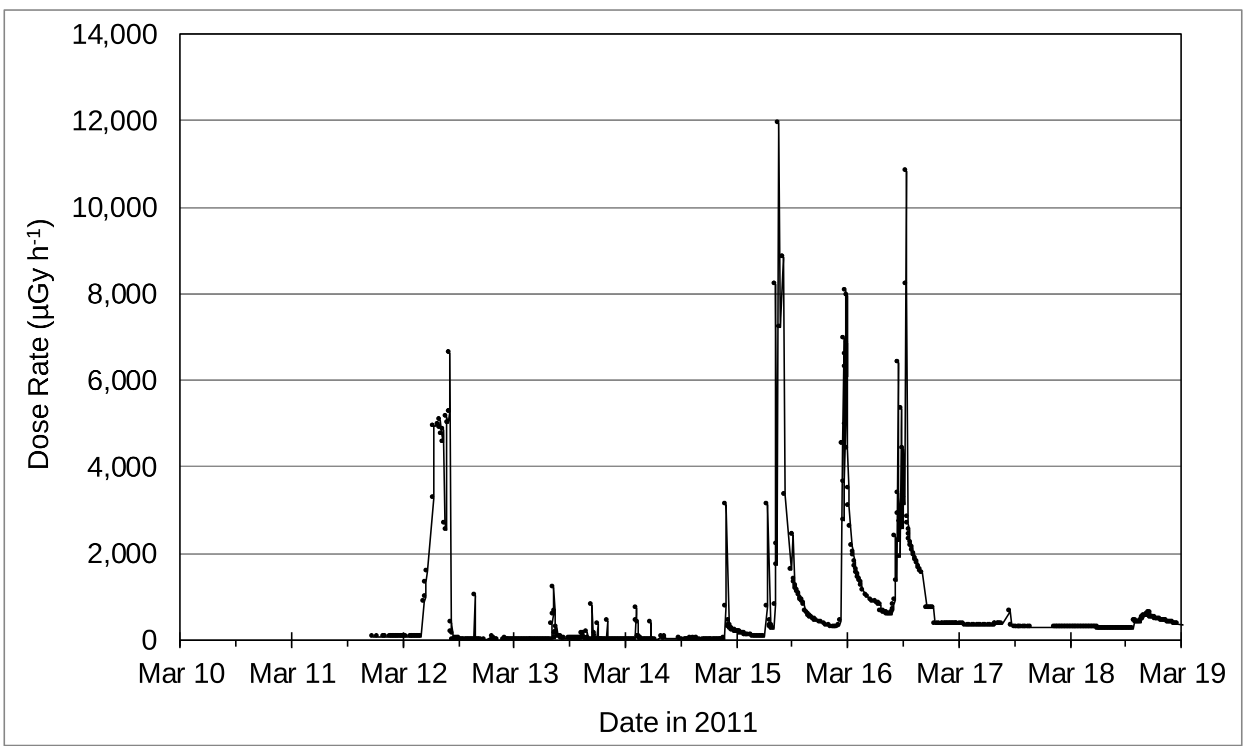


**Figure 4. TEPCO dose rate measurements for the FDNPS main gate during the first week following the accident**

The releases of radioactive materials can be transported through the air to subsequently deposit on water sources, and the land. The radioactive materials in the air and deposited on land and water can expose individuals to radiation directly in a process called external exposure. Measured radiation dose rates are indicators of the doses received. The concentrations of radioactive materials in air, water, and soil are associated with radiation dose when taken into the body by breathing air, drinking water, and ingesting soil through a process called internal exposure. Further details of the measurements of radiation and radioactive materials in these environmental media are discussed in the following sections.

## 2.3 External Radiation Monitoring

External radiation dose from atmospheric releases of FDNPS radioactive material that subsequently deposited on surfaces in occupied areas was generally the largest component of radiation dose. For large populations of individuals that did not enter the most contaminated areas, radiation doses from external sources were reconstructed using several sources of measurements of environmental gamma radiation.

The most extensive sources of environmental measurements were the MEXT monitoring stations. These stations were located in all 47 Japanese prefectures as displayed in Figure 1 and as listed in Table 4 along with city in which the station is located. A significant feature of the MEXT monitoring data is that it is continuous—it provides for a pre-accident baseline, monitoring during the radiological release, and monitoring post-radiological release.

Shore locations of principal USFJ installations and temporary operating sites during OT are also listed in Table 4 (MEXT, 2011).

Some GOJ MEXT external radiation dose monitoring stations contained energy-compensated, thallium-doped, sodium iodide [NaI(Tl)] detectors for air kerma (μGy) measurements. Gamma photon energies over 3 MeV were excluded. The NaI(Tl) detectors were housed in a protective environmental enclosure usually made of plastic or aluminum. Calibrations were performed in situ with an external mixed gamma source. However, some had Geiger-Mueller (G-M) or ionization chamber detectors as described in Sumiya et al. (2010). For the report it is assumed that equivalent or effective dose is numerically equal to air kerma reported by the MEXT systems.[6]

Figure 5 provides an example of dose rate measurements for the MEXT monitoring station in Tokyo Prefecture. Hourly measurement values are displayed for data through mid-May, while data after that time are displayed as a daily mean. Two cumulative dose lines from March 11 are plotted: one for the measured data (red-solid line) and another for a presumed pre-accident, constant dose rate (blue-dashed line) of 0.044 $\mu$Gy $h^{-1}$, which DARWG scientists determined by calculating the mean of the minimum and maximum values of pre-accident dose rates. This plot and similar ones for other MEXT measurement sets were prepared using judgment on pre-incident rates to provide a meaningful display of cumulative net dose presumed to be associated with the accident.

[6] In emergency situations the GOJ assumes that the equivalent dose in μSv = air kerma in μGy.

**Table 4. Locations of MEXT external radiation dose monitoring stations**

| Prefecture | City | Shore Location | Prefecture | City | Shore Location |
|---|---|---|---|---|---|
| Hokkaido | Sapporo | | Shiga | Otsu | |
| Aomori | Aomori | Misawa AB | Kyoto | Kyoto | |
| Iwate | Morioka | City of Ofunato* | Osaka | Osaka | |
| Miyagi | Sendai | Camp Sendai* | Hyogo | Kobe | |
| Akita | Akita | | Nara | Nara | |
| Yamagata | Yamagata | City of Yamagata* | Wakayama | Wakayama | |
| Fukushima | Futaba | J-Village* | Tottori | Tohaku | |
| Ibaraki | Mito | Hyakuri AB* | Shimane | Matsue | |
| Tochigi | Utsunomiya | City of Oyama* | Okayama | Okayama | |
| Gunma | Maebashi | | Hiroshima | Hiroshima | Kure Port |
| Saitama | Saitama | Camp Asaka | Yamaguchi | Yamaguchi | Iwakuni MCAS |
| Chiba | Ichihara | Kisarazu Aux. Field | Tokushima | Tokushima | |
| Tokyo | Shinyuku | Yokota AB | Kagawa | Takamatsu | |
| Kanagawa | Chigasaki | Atsugi NAF | Ehime | Matsuyama | |
| Niigata | Niigata | | Kochi | Kochi | |
| Toyama | Imizu | | Fukuoka | Dazaifu | |
| Ishikawa | Kanazawa | | Saga | Saga | |
| Fukui | Fukui | | Nagasaki | Omura | Sasebo NB |
| Yamanashi | Yamanashi | | Kumamoto | Uto | |
| Nagano | Nagano | | Oita | Oita | |
| Gifu | Kakamiahara | | Miyazaki | Miyazaki | |
| Shizuoka | Shizuoka | Camp Fuji | Kagoshima | Kagoshima | |
| Aichi | Nagoya | | Okinawa | Uruma | Kadena AB |
| Mie | Yokkaichi | | | | |

*Temporary location of U.S. Military Personnel

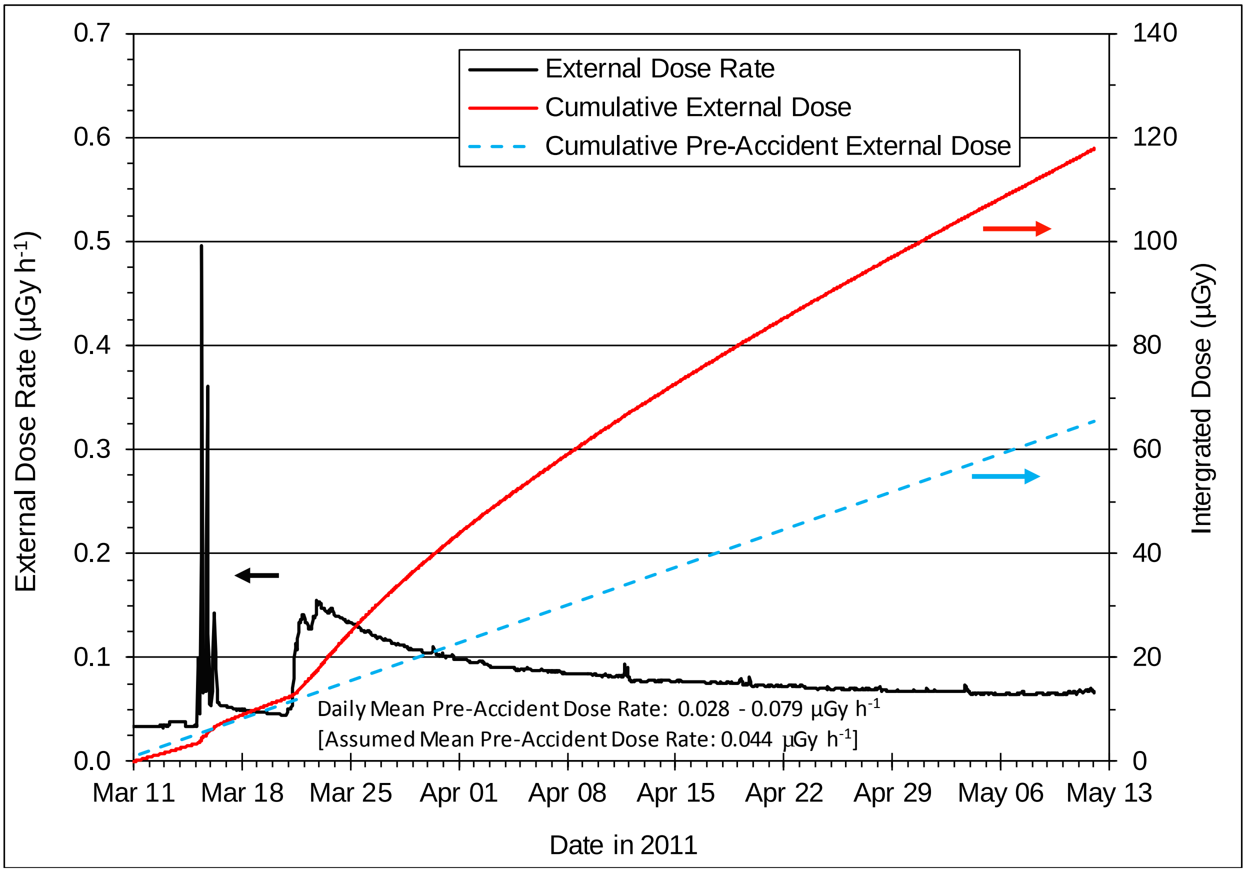


**Figure 5. External radiation dose rates and integrated doses for Tokyo Prefecture at Shinyuku**

Tokyo prefecture forms the northwestern border of Tokyo Bay and encompasses the Tokyo metropolitan area. The largest deviations from pre-accident dose rates were observed over 12 days between March 15 and 27, with the dose rate spike on March 15 likely dominated by noble gas releases from FDNPS Unit 2. After March 27, dose rate is dominated by emissions from ground-deposited radionuclides that were released by the reactor and by pre-accident existing dose rates. The relatively consistent dose rate beyond mid-May that exceeds the pre-accident dose rate is dominated by the photon emissions from residual Cs-134 and Cs-137 because other significant radionuclides released from the reactor, e.g., radioiodines and radiotelleriums, had undergone significant radiological decay.

At USFJ installations, on naval vessels, and in mission areas where DOD-affiliated individuals were located, external radiation dose measurements were made with portable radiation detection, indication, and computation (RADIAC) equipment. Most of the instruments were multifunctional, primarily designed for exposure measurements, but with the ability to accommodate optional detectors, e.g., α/β-scintillators, pancake G-M probes, γ-scintillators, and others. Extensive measurements were conducted with additional probe options during OT. Table 5 lists some of the instruments used for external radiation dose measurements (AIPH, 2011). More detailed discussions of the radiation monitoring equipment used in support of OT are provided in Appendix A.

**Table 5. DOD portable survey instruments used for the measurement of external radiation during Operation Tomodachi**

| Instrument | Type | Style | β-window | Exposure Rate Range |
|---|---|---|---|---|
| Canberra ADM-300 | Energy-Compensated G-M | Internal, Cylindrical | 3–4 mg $cm^{-2}$ | 10 μR $h^{-1}$–5 R $h^{-1}$ |
| | | | None | 5–10,000 R $h^{-1}$ |
| AN/PDQ-4 | Internal G-M | Cylindrical | None | 10 μR $h^{-1}$–1,000 R $h^{-1}$ |
| | External G-M | Cylindrical | Yes, > 670 keV | 10 μR $h^{-1}$–1,000 R $h^{-1}$ |
| AN/VDR-2<br>AN/PDR-77 | Energy-Compensated G-M | External, Cylindrical | Yes, 3–4 mg $cm^{-2}$ | 10 μR $h^{-1}$–5 R $h^{-1}$ |
| | | | None | 5–1,000 R $h^{-1}$ |
| Fluke 451P | Pressurized (6 atm) Ion Chamber | Cylindrical | None | 5 μR $h^{-1}$–5 R $h^{-1}$ |

[*]See Appendix A for specification information on instrumentation used.

There was significant variability in the frequency of measurements conducted at the different installations. Some installations collected measurements hourly for several days, while most collected measurements less frequently. At some installations, the measurement frequency changed significantly throughout the period of the accident response, with lower measurement frequencies during the latter parts of April compared to higher frequencies during the end of March. One installation started measurements on March 17, a few days after the Tokyo metropolitan area was impacted by a radioactive cloud, while some initiated measurements as late as March 28. A number of installations collected exposure measurements at multiple locations.

Although all of the survey instruments in Table 5 (except AN/PDQ-4) were capable of measuring an integrated radiation dose from external exposure over a predetermined period of time, rate mode was used for most measurements. This preferential use of rate mode may be attributed to the familiarity that most DOD users of the instrument have with this mode for operational purposes and in emergency response training. For users of G-M detectors with β-particle windows, measurements were commonly made with the window in an open position. In the presence of ground-deposited fission products, a measurement with the β-window open would normally be higher and include a higher contribution from low-energy photons than with the window closed. One installation reported paired measurements with the window open and closed. Measurements commonly were collected at waist level to approximate a one meter height above ground level (AIPH, 2011).

DOE response teams collected external radiation dose measurements at a number of locations where the teams were deployed. These measurements were collected with portable instruments to include the Canberra ADM-300. DOE measurements collected in the vicinity of a USFJ installation or DOD deployment area augmented DOD measurements for the calculation of external radiation dose rates as explained in Appendix C.

External radiation doses for PEPs (Section 3) were calculated based on a combination of compiled DOD, DOE, and MEXT data sources. DOD data were measured and compiled by USFJ, AIPH, the Air Force Radiation Assessment Team (AFRAT), and other DOD resources.

The data were entered in spreadsheets and uploaded into the Defense Occupational and Environmental Health Readiness System-Industrial Hygiene System (DOD, 2011). The DOE data were compiled by the National Nuclear Security Administration (NNSA) from DOE, DOD, as well as private sources and uploaded to the NNSA Response Data Repository (NNSA, 2011). MEXT data were compiled from published reports for each of the 47 monitoring stations. The data are reported for each hour along with the normal, pre-accident range of external radiation levels for the monitoring station (MEXT, 2011).

If DOD and DOE measurement data existed for a PEP, the maximum measured value for each hour where data existed was used in the assessment, representing the dose rate for that hour. Since DOD data were organized by location, DOD data were analyzed for all of the locations in a single PEP. For PEPs that include more than one area such as the Atsugi NAF and Yokota AB PEPs, the highest hourly external radiation dose measurement for all of the locations in the same PEP was used to represent the external radiation dose for any hour with more than one measurement. The DOE data were not organized by location, but each measurement in the database listed the latitude and longitude of all measurements. All measurements that were made near (within 10 miles) a PEP location were considered to represent the external radiation dose for that PEP location. If more than one external radiation dose measurement was made in a single hour, the highest external radiation dose measurement was used as the external radiation dose rate for that hour.

For most PEPs, because DOD or DOE measurements were not collected at regular intervals during the period of interest, external radiation dose rates were augmented with adjusted MEXT data. The MEXT data were adjusted by a factor calculated from the ratio of the maximum DOD or DOE external radiation dose rate measurement for that hour to the reported MEXT rate for the same hour. The MEXT data adjustment factor was calculated by taking the average ratio of DOD or DOE data to the MEXT data for all hours that had DOD or DOE data. The adjustment factors ranged from 1.33 to 5.12 with an average value of 3.57 (coefficient of variation [CV] of 32 percent) over the 13 different general locations for which they were calculated. For the few hours when MEXT data were not available, either the average background was used if the missing value was in the first two days after March 11 or the higher of the two measurements on either side of the missing hour was used to fill in the missing data. This was especially important for initial releases from the FDNPS in about the first two weeks when external radiation dose may not have been monitored at USFJ installations. Additional details about the number of DOD and DOE measurements used can be found in Section 2.10.

After the data were compiled to provide an external radiation dose rate value for each hour of the 60-day period, the dose rates were plotted to assist in identifying any transcription errors or other anomalies. Any data point that was significantly higher or lower than other data points was reviewed. The original DOD and DOE results were reviewed to determine if there were any transcription errors, and any such errors were corrected with original data and the data were recombined.

Figure 6 displays the external radiation dose rate measurements at the closest DOE monitoring point on or near Yokosuka NB (D-8), and the adjusted MEXT external radiation dose

rate measurements from its monitoring station at Chigasaki City (Kanagawa Prefecture). The two data sets were combined into a composite, fitted data set for the PEP so that there was an external radiation dose rate value for each hour. The data consist of the maximum DOE field measurements during any hourly measurement period combined with adjusted MEXT data for hourly periods for which there were no DOE measurements. In addition, for each of the DARWG Locations, except J-Village (D-5), Table 6 lists the prefecture of the corresponding MEXT Station and the adjustment factor applied to MEXT external dose rate measurements. In addition, Appendix F provides exposure rate plots for each of those 13 DARWG Locations. Details explaining the development of DARWG locations are provided in Section 2.8.

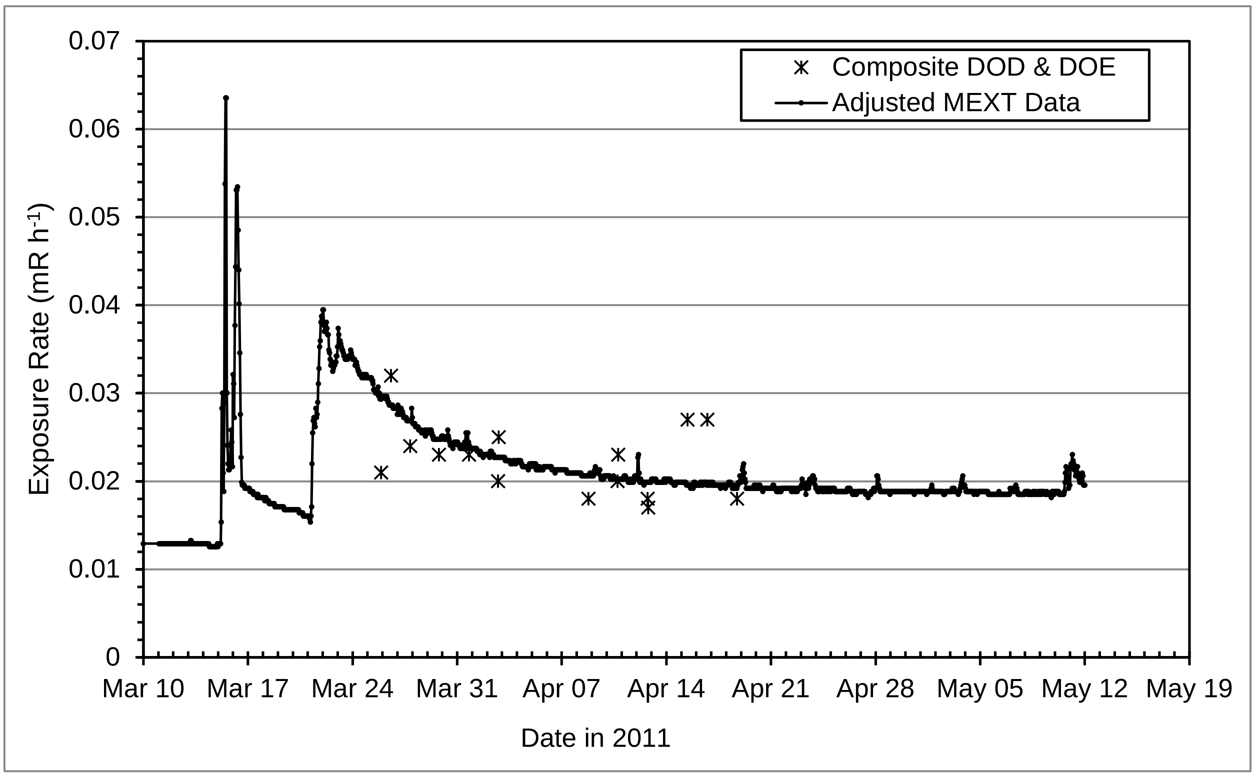


**Figure 6. Adjusted MEXT data (Kanagawa Prefecture) and DOE data for Yokosuka NB**

The variations among DOD, DOE, and MEXT data are believed to be the result of a number of factors, including detector height, ground/surface/structural composition beneath the detector, lower level of detection, and differing procedures and methods. First, the MEXT station detectors were at various heights above ground level. For some emplacements, the heights were near ground level, which is similar to the one-meter height that was commonly used by DOD and DOE survey teams for their portable instrument measurements. This was the case for the MEXT monitoring station in Fukushima Prefecture, which is positioned 2.5 meters above ground level as shown in Figure 7. However, for some locations, emplacements were clearly on the roofs of buildings such as the MEXT station in Tokyo Prefecture shown in Figure 8. Although this station

is well above ground level, other roof-top stations were much closer to ground level, as illustrated by the MEXT station in Kanagawa Prefecture (Figure 8).

**Table 6. External exposure adjustment factors of selected MEXT fixed monitoring point detectors**

| Shore Location (DARWG Location Number) | Closest MEXT Station (Prefecture) | Adjustment Factor to MEXT Exposure Rates |
|---|---|---|
| Misawa AB (D-1) | Aomori (P-2) | 5.12 |
| Camp Sendai (D-2) | Miyagi (P-4) | 4.32 |
| City of Ishinomaki (D-3) | Miyagi (P-4) | 2.85 |
| City of Yamagata (D-4) | Yamagata (P-6) | 4.73 |
| Hyakuri AB (D-6) | Ibaraki (P-8) | 1.33 |
| City of Oyama (D-7) | Tochigi (P-9) | 3.19 |
| Yokota AB (D-8) | Tokyo (P-13) | 4.10 |
| Hardy Barracks (D-9) | Tokyo (P-13) | 2.81 |
| Atsugi NAF (D-10) | Kanagawa (P-14) | 4.72 |
| Yokosuka NB (D-11) | Kanagawa (P-14) | 3.49 |
| Camp Fuji (D-12) | Shizuoka (P-22) | 4.47 |
| Iwakuni MCAS (D-13) | Yamaguchi (P-35) | 1.90 |
| Sasebo NB (D-14) | Nagasaki (P-42) | 3.37 |

**Figure 7. MEXT external radiation dose monitoring station in Fukushima Prefecture (2.5 meters above ground level)**


**Figure 8. MEXT external radiation monitoring stations in Tokyo and Kanagawa Prefectures**

As summarized in Table 7, detector height could have a variable effect on measured doses from normal and accident-related contributions to external radiation exposure. For cosmic and cloud debris contributions, detector height will only have a minor influence on measured dose, whereas measured dose from terrestrial sources and deposited fallout can be highly influenced by detector height. Detectors at greater heights would report lower dose rates from terrestrial sources of exposure due to air attenuation. For detectors placed on roofs, the building would provide additional attenuation compared to air but could contribute to the external radiation dose rate from naturally occurring radioactive material (NORM) inherent to building materials.

The type of ground surface over which measurements were conducted also impacts measured dose, as detailed in Table 7. Many of the external radiation dose measurements documented by DOD had details on characteristics of the measurement locations, e.g., grassy area, asphalt, etc. Although grassy areas would have a greater tendency to retain deposited radioactive materials, materials deposited on building roofs where external radiation dose monitoring stations were located would have behaved in a manner similar to that of a ground-based monitoring station if there was sufficient retention on the roof surface. Retention would have been impacted by the type of roof surface, precipitation, drainage characteristics of the roof, and removal by wind. In addition, for those MEXT stations equipped with NaI(Tl) detection systems, radiation interaction events with energy depositions greater than 3 MeV were not included in MEXT external dose. This method effectively limited incorporation of the majority of the cosmic radiation dose. In contrast, measurements with ion chambers and energy-compensated G-Ms would include these contributions.

During the data validation process used for the dose calculations for this report, the accuracy of portable instruments for measuring external radiation dose and the measurement practices of survey team personnel were evaluated. Many of the portable instruments used by DOD for external radiation dose measurements were designed and calibrated to provide accurate measurements at exposure levels higher than those encountered at many of the USFJ

installations, which had only small increases over pre-accident external radiation dose conditions. The use of DOD portable instruments likely resulted in higher reported external radiation dose, which therefore were conservative.

**Table 7. Key factors affecting response of detectors to external radiation dose**

| Factor | Sources | | | |
|---|---|---|---|---|
| | Normal External Radiation Dose | | Accident-Related Contributions to External Radiation Dose | |
| | Cosmic | Terrestrial | Radioactive Cloud | Fallout Deposition |
| Detector Height | Minor differences | Lower reported reading for greater heights due to attenuation of air, structure provides additional attenuation, but provides some contribution from NORM | Minor differences | Reported result depends on distance between deposition surface and detector—similar to characteristics of the terrestrial source. For detectors on building roof-tops, separation distance may be similar to a ground-based detector if roof surface retained fallout. If detector is on elevated tower, influence will be dominated by ground-based deposition, but subject to decreased reported result for towers of greater height. |
| Ground/Surface/ Structural Composition | None | Paved surfaces generally provide lower external radiation levels than soiled areas, unless comprised of high NORM | None | Dependent on the retention characteristics of the surface. Heavily vegetated areas, in general, will have the greatest retention, with paved surfaces the lowest. Deposition on paved surfaces is readily translocated by wind and surface water flows to soiled/vegetated areas with greater retention characteristics. |

To evaluate this issue, measurements of external radiation surveys were conducted at the AF Safety Center, Kirtland AFB (Albuquerque, NM) with a Fluke 451P and ADM-300 meter,

both having current calibrations. Both instruments were operated in dose (or exposure) integration mode for 130 minutes in outdoor and indoor measurement locations. For both sets of measurements, the ADM-300 reported approximately twice the mean exposure rates recorded by the 451P—12 and 12.5 $\mu R\ h^{-1}$ for indoor and outdoor measurements. The 12.5 $\mu R\ h^{-1}$ exposure rate is similar to the combined cosmic and terrestrial exposures expected for Albuquerque, NM (Gollnick, 1988; Phillips et al., 1993). Based on this information, there is an expectation that measurements made with the ADM-300 and AN/PDR-77 at low external radiation dose levels will be biased toward higher results. Although integrated exposure measurements performed with the 451P may be reasonably accurate in the low exposure rate range, statistical fluctuations in the digital display when the instrument is used in the rate mode of operation coupled with measurement technique may have caused operators to report exposure rates that were biased toward higher values. In this test, the 451P's digital exposure rate readings were recorded with the instrument exposed to radiation fields of normal background and a series of higher exposure rates created with a Cs-137 check source placed at various distances to the detector.

Figure 9 provides the results from the measurement tests. The abscissa represents the mean exposure rate for each trial, while the left ordinate represents measured exposure rate for the displayed curves of minimum, median, and maximum exposure rate from the instrument for each measurement trial. As expected, the CV decreased as the mean exposure rate increased. Among the 66 measurements recorded for the lowest mean exposure rate measurement trial, the maximum value was 2.3 times the mean for the data set. It is a common practice for individuals conducting measurements with portable instruments to record the highest value observed on a digital display, which clearly could introduce measurement bias and would be expected to be much higher at the lowest range of exposure rate. The potential bias from the use of the Fluke 451P at low exposure rates is highly dependent on how the individual surveyor performs each survey. As a consequence, the dose assessments were performed using the highest credible measurements available for a given location, thus minimizing the impact of any potential bias.

DOE and Japanese agencies conducted aerial monitoring and ground-level measurements with high-resolution $\gamma$-spectrometry systems to assess isotopic composition of ground-deposited radionuclides. The majority of these measurements were conducted at locations close to the FDNPS. The primary purpose of these measurements was to assess areas with the highest concentrations of deposited radionuclides for decisions on future use restrictions. Although the results of these measurements were evaluated, they are not a useful direct indicator of temporal variations in external radiation dose for PEP categories, and were not used in dose calculations for this report. Qualitatively, however, the data were very useful as supporting information on relative rates of fallout deposition density and expected external radiation dose rates in affected areas.

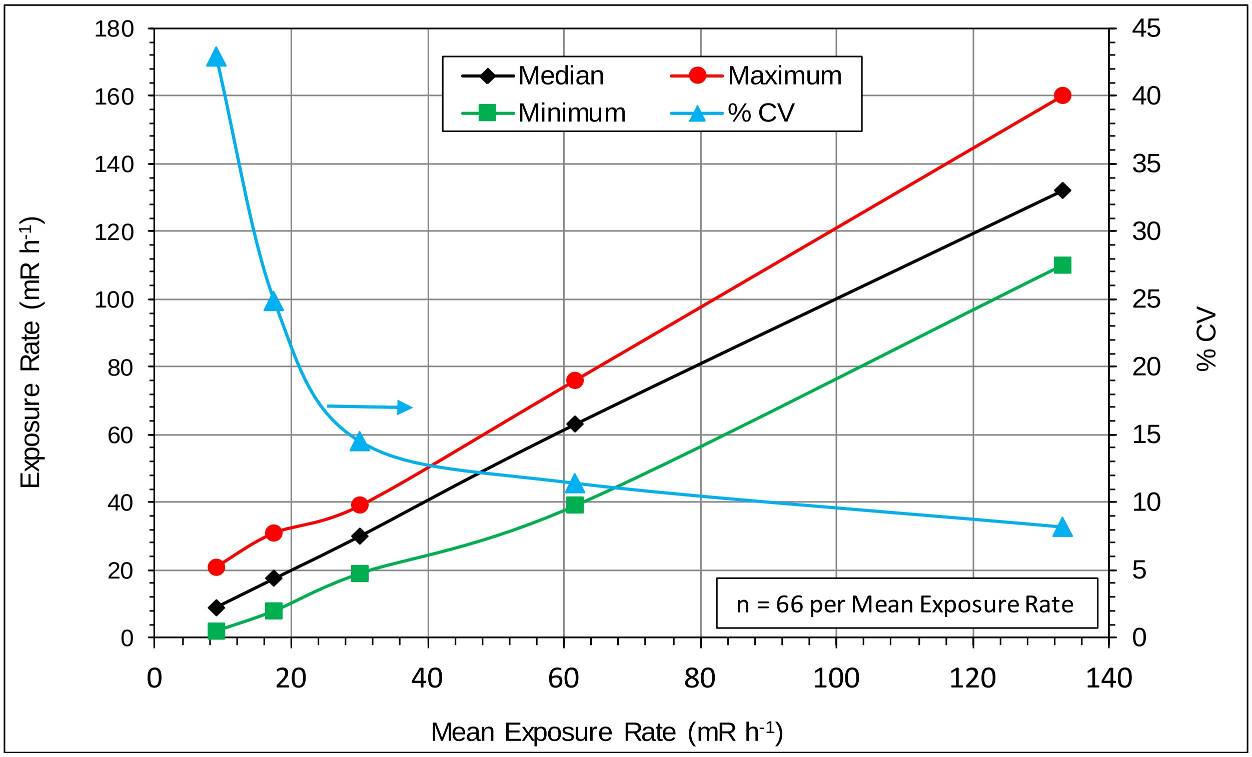


**Figure 9. External exposure rates measured with a Fluke 451P at various applied exposure rates**

### 2.4 Air Monitoring

DOD and DOE accident response teams performed extensive air sampling using fixed sampling stations at several locations. As was observed for external radiation dose rate measurements, there was variability in air sampling equipment and methodologies. Some air sampling was conducted at many of the USFJ installations, on naval vessels, and in mission areas where DOD-affiliated individuals were located.

Nuclear reactor accidents can lead to increased temperatures and pressures in containment barriers that exceed reactor design parameters and result in the release of radioactive materials. The materials released to the environment under these conditions can contain a complex mixture of radionuclides that are in the reactor core at the time of the accident but are expected to be dominated by noble gases, radioiodines, radiocesiums, and radiotelleriums because of the low boiling points of these elements and related greater potential for release to the air compared with those in solid and liquid physical phases. Once released to the environment the latter three groups of elements are subject to chemical and physical state changes. Among these elements, sampling for radioiodines is more complex because the materials may exist in a gaseous or aerosol form, while the radiocesiums and radiotelleriums are normally aerosols.

In environmental sampling for radioiodines, it is customary to use in-line sampling with a glass-fiber filter to remove aerosol and activated charcoal granules to adsorb gaseous iodine compounds. This sampling method was performed by many of the U.S. radiological emergency teams responding to the Fukushima reactor accident. Although this method is very useful for

radioiodines, it has some shortcomings for the sampling of other radionuclides. Due to the limitations in chemical bonding sites and affinity of these sites for binding water vapor, there are practical limits on the volume of air that can be sampled on a single canister. In addition, lower flow rates must be used with these filter/canister systems than those possible for glass-fiber filter-only systems, because there is the potential for "break-though" in the activated charcoal canister at higher flow rates. As a result, low-volume sampling and subsequent analysis of aerosol filter/charcoal canisters by high-resolution $\gamma$-spectrometry may not have provided sufficient sensitivity for some radionuclides expected in the atmosphere from the accident.

Analysis of air samples presents an additional challenge for producing comprehensive results. Many of the important radionuclides are photon emitters and are readily quantified with $\gamma$-spectrometry systems; however most of the USFJ installations were not equipped to perform such analyses thereby limiting the quantification of photon-emitting radionuclides with shorter half-lives. For most filter analyses, time delays between sampling and analysis limited detection sensitivity for some short-lived radionuclides, e.g., iodine-133 (half-life of 20 h), and tellerium-129 (half-life of 1.1 h).

Table 8 lists the typical air-sampling equipment used by DOD and DOE. With the exception of the custom-manufactured, high-flow rate, air sampling system that is used at the IMS, the other pieces of equipment listed in the table are portable. The table lists the users of the instrumentation during the operations, the filter media used, and operating specifications. Figure 10 provides a photograph of the IMS custom high-flow rate air sampler.

Sampling frequency and sample analyses varied by installation and equipment type. The IMS station, for example, operated continuously, with individual sampling durations of 24 hours, and sample analysis conducted at a preset time following completion of each sampling period. Since there could be substantial radioactive decay of radionuclides during these extended sample collection durations, all air sample measurements were corrected for decay during sampling. USAF Bioenvironmental Engineering (BE) personnel at Yokota and Misawa ABs sampled for particulates and screened filter papers post sampling with a BP-100 pancake G-M probe and an AP-100 $\alpha$-scintillator probe, which were both used with the ADM-300 meter. A sampling volume of 1,000 $ft^3$ was the desired amount. After screening, filter samples were sent to USAF School of Aerospace Medicine (USAFSAM), Wright-Patterson AFB, OH for analysis.

The AIPH deployed to Japan for the operation and conducted air sampling at Camp Zama. Using methods that were similar to those used by the USAF BEs, samples were screened post sample collection with portable instruments and sent to AIPH, Aberdeen Proving Ground, MD for high-resolution $\gamma$-spectrometry analysis. Isotopic analyses were compared to screening measurements, allowing a correlation to be established. This allowed predictions of concentrations on future samples that were screened, yet had not undergone laboratory analysis. USN personnel on ships and USFJ installations conducted air sampling, with portable instrument screening. However, because the standard sample volume collected was 1 $m^3$, insufficient activity would have been collected at distant sampling locations, i.e., Tokyo metropolitan area installations, for quantification by high-resolution $\gamma$-spectrometry. AFRAT collected air samples at multiple locations during the operation. These samples were analyzed by the AFRAT field laboratory with high-resolution $\gamma$-spectrometry.

Table 8. DOD and DOE air sampling systems

| Sampling System* | User | Filter Media | Operating Specifications |
|---|---|---|---|
| Hi-Q Model CF-995B | AFRAT | - Glass Fiber & In-line Activated Charcoal Canister | - AC & Battery Power Sources<br>- Adjustable Flow Rate<br>- User Selected Sampling Times<br>- Portable |
| F&J Digital Model DFHV-1 | AFRAT<br>DOE | - Glass Fiber & In-line Activated Charcoal<br>- Glass Fiber | - AC Power Source<br>- Adjustable Flow Rate<br>- User Selected Sampling Times<br>- Portable |
| RADēCO Model H-809VII | USAF:<br>Yokota AB,<br>Misawa AB | - Glass Fiber | - AC Power Source<br>- Adjustable Flow Rate<br>- User Selected Sampling times<br>- Portable |
| Custom Manufactured High Flow | USAF:<br>Yokota AB<br>Misawa AB<br><br>IMS | - Glass Fiber | - AC Power Source<br>- User Selected Sampling Duration<br>- Build-in, high-resolution $\gamma$-spectroscopy counting system<br>- Automated sampling changing |
| Hi-Q Model TFIA | USA<br>Camp Zama | - Glass Fiber | - AC Power Source<br>- User Selected Sampling Duration<br>- Portable |
| RADēCO Model H-810 | USA<br>Camp Zama | - Glass Fiber | - AC Power Source<br>- User selected sampling volumes<br>- Portable |
| RADēCO Model HD-1151/PD | USN | - Glass Fiber | - Battery Operated<br>- User selected sampling volumes<br>- Portable |

*See Appendix A for specification information on instrumentation used.

**Figure 10. IMS custom high flow sampler**

For illustrative purposes, the results for one of the high-volume air samples collected on Yokota AB (149 miles from FDNPS) are provided in Table 9. This sample contains two sets of results: one from the built-in high resolution, γ-spectrometry system and the other from laboratory analysis at Los Alamos National Laboratory (LANL). The results of the two analyses are comparable for reported concentrations; however, due to the inherently superior shielding of the LANL laboratory detection system and longer counting period, lower uncertainties were achieved for these results compared to the field analyses. Furthermore, due to these characteristics, Mo-99 and La-140 were reported by LANL, but had concentrations below the reporting level of the field analysis. Although these advantages of laboratory analysis at LANL were gained, some short-lived radionuclides could not be detected because of the delays in transport. For this sample, I-133 (half-life of 20 h), Tc-99m (half-life of 6 h), and Te-129 (half-life of 1.1 h) were quantified in the field analysis but not in the laboratory.

**Table 9. USAF high-volume air sampling (aerosols) results on Yokota AB**

| | | | | | |
|---|---|---|---|---|---|
| **Start** | Date = | Mar-18 | | | |
| | Time = | 1309Z | | | |
| **Stop** | Date = | Mar-19 | | | |
| | Time = | 0109Z | | | |
| Sampling Time (h) = | | 12 | | | |
| | | **Ground-Level Air Sample** | | | |
| **Radio-nuclide** | **Half-life** | **Field Detector Result** | | **Laboratory Result** | |
| | **y** | **μBq m$^{-3}$** | **% CV (1 σ)** | **μBq m$^{-3}$** | **% CV (1 σ)** |
| Ba-136m | 1.00E-08 | | | | |
| Ba-140 | 0.035 | | | | |
| Cs-134 | 2.05 | 5.19E+03 | 7.8 | 5.98E+03 | 0.7 |
| Cs-136 | 0.0375 | 9.44E+02 | 9.7 | 1.13E+03 | 1.8 |
| Cs-137 | 30.0 | 6.06E+03 | 8.2 | 6.35E+03 | 1.1 |
| I-130 | 0.0014 | | | | |
| I-131 | 0.022 | 1.47E+05 | 6 | 1.07E+05 | 0.7 |
| I-132 | 0.00026 | 1.30E+04 | 8.3 | 1.62E+04 | 0.9 |
| I-133 | 0.0023 | 1.22E+03 | 8.5 | | |
| La-140 | 0.11 | | | 2.75E+02 | 9.7 |
| Mo-99 | 0.0076 | | | 5.88E+02 | 17 |
| Tc-99m | 0.00069 | 1.26E+03 | 4.8 | | |
| Te-129 | 0.000131 | 3.05E+03 | 17 | 0.00E+00 | |
| Te-129m | 0.093 | 6.61E+03 | 38 | 7.10E+03 | 56 |
| Te-131m | 0.000047 | | | | |
| Te-132 | 0.0089 | 1.80E+04 | 6.5 | 1.82E+04 | 4.7 |
| Nb-95 | 0.096 | | | | |

During the first nine days of high volume air sampling at Yokota AB, filter papers were analyzed with the field detector and at LANL. Laboratory processing to supplement field analyses was initially prompted by experiences of high dead times in the counting system for some samples with high activity concentrations. High dead times can lead to greater uncertainties and bias in reported results because high event rates can cause several effects in signal processing and spectrometric systems that are not easily compensated. Therefore, analysis after the time delays in transporting samples to the LANL's laboratory allowed dead-time effects to be reduced, thereby producing results that were preferred to the results reported by the field analysis system.

Along with this decision to analyze some samples at LANL, a decision was made to perform chemical separations and isotopic analyses for strontium, cerium, and plutonium. With the exception of Sr-89, other isotopes of strontium, cerium and plutonium were below reporting levels for the method. Table 10 provides a summary of activity concentrations for key radionuclides and strontium isotopes among the only four samples that had reported concentrations of Sr-89. In general, the release fractions of refractory fission products from the core of the reactor are substantially lower than those of radiocesiums, radiotelleriums, and radioiodines. The Sr-89 to Cs-137 activity ratio in a reactor core at the time of a hypothetical accident is estimated at about 20 in NUREG-0956 (NRC, 1986), compared with the highest ratio from the Yokota AB sample taken on March 14 (0.0044), which was about 4,500 times lower. These data provided clear evidence that refractory elements in the core of the reactor were released to the atmosphere as small fractions of the more volatile cesium. In addition to the chemical separation and analyses accomplished at LANL to assess refractory isotope contributions to sampled aerosols, Ba-140 can be used as a surrogate for strontium releases because both elemental forms have similar melting points (strontium at 1041°C and barium at 1002°C) and form compounds with similar chemical characteristics; i.e., both are alkaline earth metals. Barium-140 was quantified by high-resolution γ-spectrometry in a number of the Yokota AB high-volume air samples, as listed in Table 10.

**Table 10. Radioactive material concentrations (μBq $m^{-3}$) for key radionuclides and strontium isotopes for high volume air sampling at Yokota AB, Japan**

| Sampling Date | I-131 ($t_{1/2}$*, 8.05 d) | Cs-134 | Cs-137 | Sr-89 ($t_{1/2}$, 52.6 d) | Sr-90 | Ratios | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | Sr-89 / Sr-90 | Sr-89 / Cs-137 | I-131 / Cs-137 |
| Mar 14 | $1.9 \times 10^7$ | $6.6 \times 10^6$ | $6.3 \times 10^6$ | $2.80 \times 10^4$ | $<1 \times 10^5$ | > 0.28 | 0.0044 | 3.0 |
| Mar 15 | $3.5 \times 10^6$ | $9.6 \times 10^5$ | $9.8 \times 10^5$ | $3.2 \times 10^3$ | < 2910 | > 1.1 | 0.0033 | 3.6 |
| Mar 20 | $4.4 \times 10^6$ | $1.8 \times 10^6$ | $2.0 \times 10^6$ | $1.0 \times 10^3$ | < 2330 | > 0.44 | 0.00052 | 2.3 |
| Mar 20 | $3.1 \times 10^6$ | $1.9 \times 10^6$ | $1.8 \times 10^6$ | $4.2 \times 10^2$ | < 2100 | >0.20 | 0.00023 | 1.7 |

*$t_{1/2}$: half-life

The Ba-140 to Cs-137 activity ratio in a reactor core at the time of a hypothetical accident is estimated at 34 per NUREG-0956 (NRC, 1986). All ratios listed in Table 11 are lower than the value cited in NUREG-0956 and somewhat consistent if Ba-140 concentrations are corrected for decay back to March 11 when the reactors became sub-critical, although the ratio reported for March 19 seems inconsistent with the other measurements. Similar to the Sr-89 data discussed above, fractional releases of Ba-140 from the reactor cores are much lower than Cs-137.

NUREG-0956 states that the theoretical activity ratios are nearly the same for Ba-140/Cs-137 and Sr-89/Cs-137, i.e., 34 and 20 respectively. This allows a measurement of either Ba-140 or Sr-89 activity to be used to estimate the activity of the other. Since Sr-89 only emits β particles, which cannot be detected by γ-spectrometry, Ba-140 was used an indicator of the presence of other elements of that NUREG-0956/1465 radionuclide element group, e.g., Sr-89.

**Table 11. Radioactive material concentrations (μBq $m^{-3}$) for Ba-140 and key radionuclides from high-volume air sampling at Yokota AB**

| | | | | | | Ratios | |
|---|---|---|---|---|---|---|---|
| **Sampling Date** | **Analysis** | **I-131 ($t_{1/2}$* 8.05 d)** | **Cs-134** | **Cs-137** | **Ba-140 ($t_{1/2}$, 12.8 d)** | **Ba-140 / Cs-137** | **I-131 / Cs-137** |
| Mar 13–14 | LANL | 9680 | 2180 | 2470 | 483 | 0.196 | 3.9 |
| Mar 14–15 | LANL | $1.9 \times 10^7$ | $6.6 \times 10^6$ | $6.3 \times 10^6$ | $7.2 \times 10^5$ | 0.114 | 3.0 |
| Mar 15–16 | LANL | $3.5 \times 10^6$ | $9.8 \times 10^5$ | $9.6 \times 10^5$ | $9.0 \times 10^4$ | 0.094 | 3.6 |
| Mar 16–17 | LANL | $6.8 \times 10^4$ | $7.3 \times 10^3$ | $7.5 \times 10^3$ | 308 | 0.041 | 9.1 |
| Mar 18 | LANL | $6.9 \times 10^4$ | $1.1 \times 10^4$ | $1.2 \times 10^4$ | 560 | 0.047 | 5.8 |
| Mar 19 | LANL | $9.2 \times 10^4$ | 5720 | 6280 | 3180 | 0.506 | 15 |
| Mar 28 | Field | $8.1 \times 10^4$ | $2.0 \times 10^4$ | $2.3 \times 10^4$ | 454 | 0.020 | 3.5 |
| Apr 6 | Field | $1.3 \times 10^4$ | 7100 | 8490 | 131 | 0.015 | 1.5 |
| Apr 7 | Field | $1.3 \times 10^4$ | 9620 | $1.1 \times 10^4$ | 132 | 0.010 | 1.2 |
| Apr 9–10 | Field | $2.2 \times 10^4$ | $2.7 \times 10^4$ | $3.1 \times 10^4$ | 693 | 0.022 | 0.71 |
| Apr 10 | Field | 9310 | 9070 | $1.0 \times 10^4$ | 104 | 0.010 | 0.93 |
| Apr 11–12 | Field | 5960 | 7860 | 9500 | 143 | 0.015 | 0.63 |
| Apr 18–19 | Field | 7050 | 8550 | 9750 | 88 | 0.009 | 0.72 |
| Apr 19–20 | Field | $1.1 \times 10^4$ | $1.5 \times 10^4$ | $1.7 \times 10^4$ | 190 | 0.011 | 0.65 |
| Apr 20–21 | Field | 8920 | $1.3 \times 10^4$ | $1.5 \times 10^4$ | 138 | 0.009 | 0.59 |

*$t_{1/2}$: half-life

Figure 11 contains a plot of Cs-137 and I-131 air concentrations from the high-volume air sampling conducted at Yokota AB. Airborne I-131 aerosol concentrations shortly after the accident began were higher than the Cs-137 in all samples.

However, by the latter part of March, as I-131 concentrations decreased due to its significantly shorter half-life, Cs-137 concentrations exceeded I-131 concentrations for a number of samples. By mid-April, I-131 concentrations were always lower than Cs-137 concentrations. For many of the samples collected in May and June, I-131 was not detectable, as shown by the absence of data points for I-131 on the plot. By the end of May, Cs-137 concentrations were somewhat stable. DARWG speculated that these concentrations were largely a result of re-suspension of deposited fallout. Over time, these concentrations will become lower as radiocesiums adsorb on minerals in soil, migrate to greater depths in the soil matrix, translocate to other parts of the ecosystem, and undergo radioactive decay.

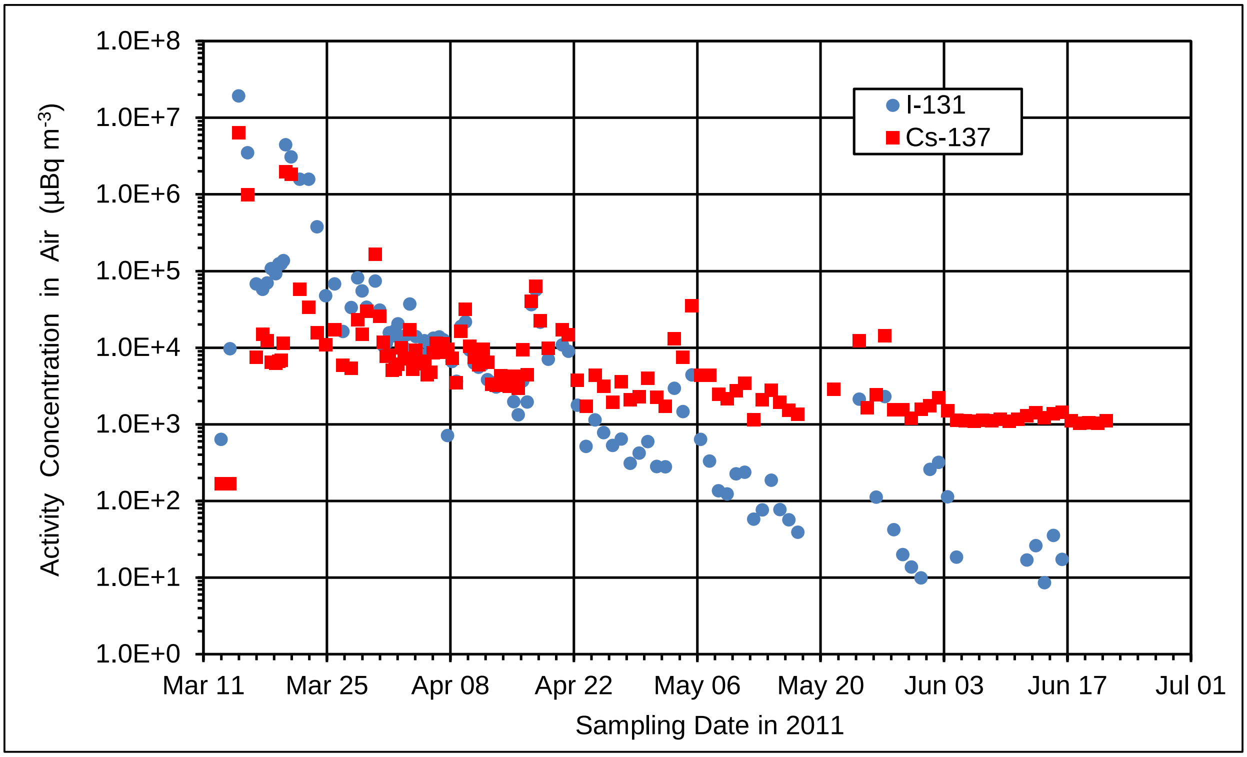


**Figure 11. Activity concentrations of I-131 and Cs-137 from USAF high-volume air sampling at Yokota AB, aerosol filtration**

DOE performed high-volume air sampling at a number of locations in Japan, but performed more low-volume sampling with in-line glass fiber/charcoal canisters. The greatest degree of sampling was conducted at Yokota AB and the U.S. Embassy in Tokyo. Dependent on the sampling date, most samples had quantifiable concentrations of Cs-137, Cs-134, and I-131. Samples that had unquantifiable concentrations of either cesium isotope were typically the charcoal canister, as the glass fiber filters were efficient in its removal. At later sampling dates in mid- to late-April, filters and canisters more commonly did not have quantifiable concentrations of I-131, which had undergone substantial radioactive decay due to its radiological half-life of 8.05 days. Figure 12 and Figure 13 show comparisons of total sampled I-131 to that collected on the glass fiber filter part of the filter combination for Yokota AB and the U.S. Embassy, respectively. The figures contain annotations of the time and concentration-weighted mean aerosol fractions. The U.S. Embassy data set had a weighted mean aerosol fraction approximately one-third of the total, while for the Yokota AB data set the weighted mean was about one half. Substantial variability is observed in the data at each location. The fluctuations in iodine concentrations are based on temporal variability in airborne release rates from the reactor and atmospheric conditions. Due to the proximity of the two air sampling locations, the total iodine concentrations have similar temporal trends. The variability in partitioning between aerosol and gas fractions is believed to be based in part on the temporal variability in releases from the reactor(s), but more importantly from chemical changes in iodine compounds during atmospheric transport and differences in dry and wet deposition plume depletion processes. The air sampling data at Yokota AB had a greater degree of variability in aerosol fraction

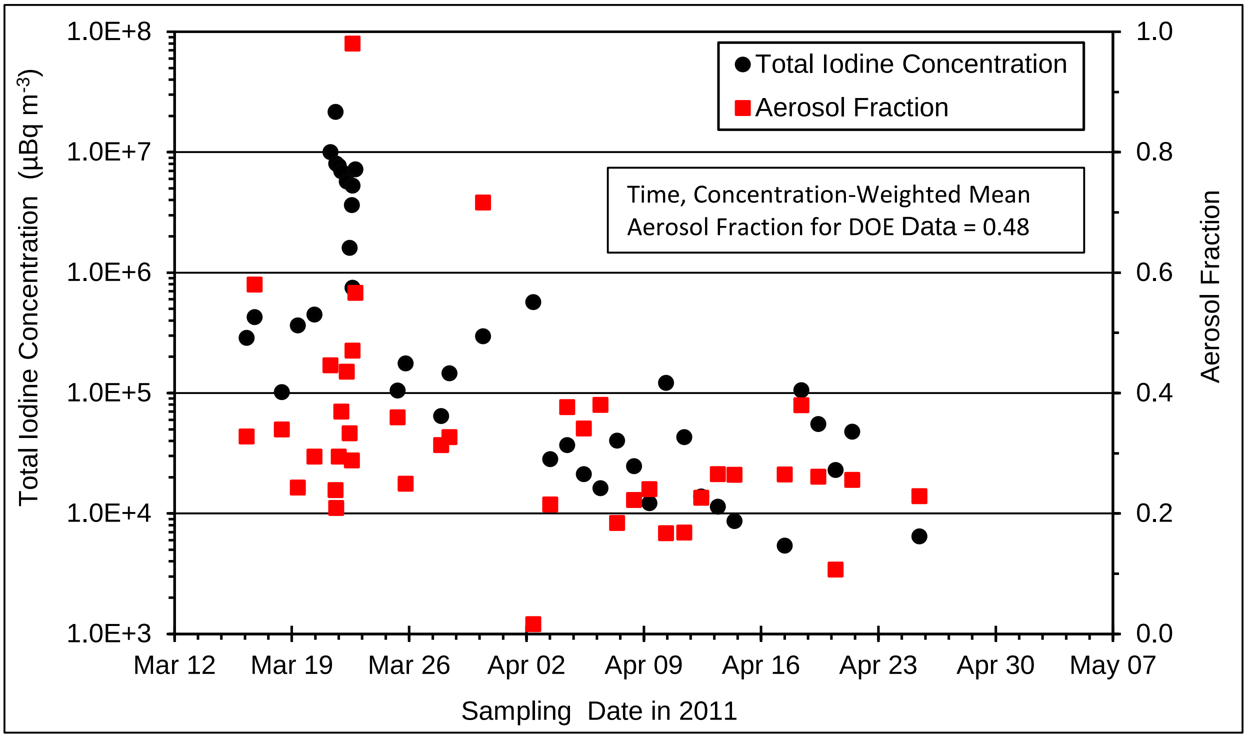


**Figure 12. I-131 concentrations at Yokota AB from DOE low-flow rate air sampling**

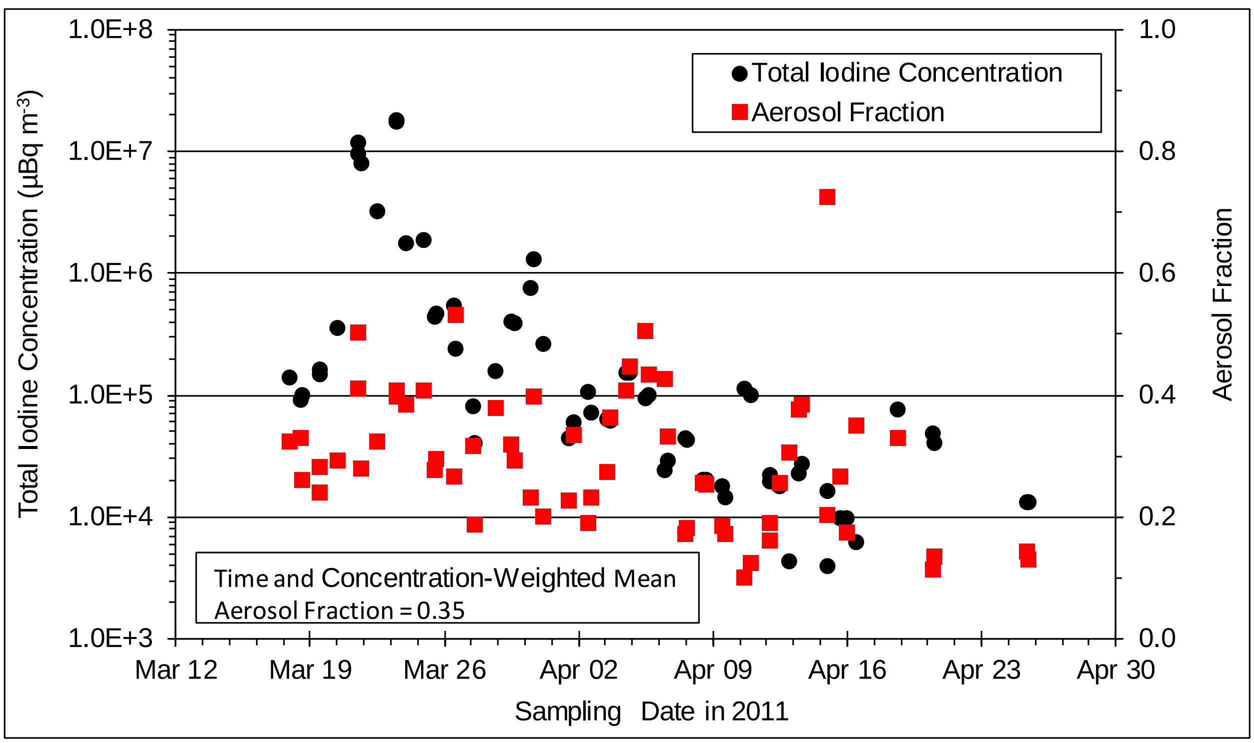


**Figure 13. I-131 concentrations at U.S. Embassy from DOE low-flow rate air sampling**

compared to U.S. Embassy data based on a visual inspection of the data, although only a few data points had extreme values compared to the typical observation.

The time and concentration-weighted gas to aerosol ratio value from the U.S. Embassy data was determined to be 1.88 ± 0.32 (1 $\sigma$). The DARWG used the upper 95 percent confidence value (2.507) of this ratio to estimate concentrations of gaseous iodine. DCs for gaseous elemental and organic (methyl iodide) chemical forms of iodine (ICRP, 2001) are listed in Table 12. The whole body effective and thyroid organ DCs for the elemental chemical form are about 27 percent higher than organic (methyl iodide) form. The actual differences vary slightly among the various age groups. While air sampling and analysis methods used were not capable of differentiating the chemical form of gaseous I-131, the DARWG's review of Nair et al. (2000) and OECD (2007) led to conclusions that air sampling at long distances from the reactor (i.e., ~145 miles for the U.S. Embassy and Yokota AB, gaseous I-131 would be predominantly in organic chemical form rather than elemental form. Although DARWG believes that gaseous iodine is almost entirely in organic form, to account for the higher values of DCs for elemental iodine, the DARWG made the conservative assumption that one-third of the gaseous I-131 was in an elemental form and two-thirds in the organic form. This assumption was applied to the other isotopes of iodine.

**Table 12. Ratios of dose coefficients of gaseous elemental iodine to methyl iodide**

| **Whole Body Effective Dose* ($Sv\ Bq^{-1}$)** | | | |
|---|---|---|---|
| **Age Category** | **Elemental Iodine** | **Methyl Iodide** | **Ratio** |
| Adult | 2.0E-08 | 1.5E-08 | 1.33 |
| 15 y | 3.1E-08 | 2.4E-08 | 1.29 |
| 10 y | 4.8E-08 | 3.7E-08 | 1.30 |
| 5 y | 9.4E-08 | 7.4E-08 | 1.27 |
| 1 y | 1.6E-07 | 1.3E-07 | 1.23 |
| 3 mo | 1.7E-07 | 1.3E-07 | 1.31 |
| **Thyroid Dose* ($Sv\ Bq^{-1}$)** | | | |
| **Age Category** | **Elemental Iodine** | **Methyl Iodide** | **Ratio** |
| Adult | 3.9E-07 | 3.1E-07 | 1.26 |
| 15 y | 6.2E-07 | 4.8E-07 | 1.29 |
| 10 y | 9.5E-07 | 7.4E-07 | 1.28 |
| 5 y | 1.9E-06 | 1.5E-06 | 1.27 |
| 1 y | 3.2E-06 | 2.5E-06 | 1.28 |
| 3 mo | 3.3E-06 | 2.6E-06 | 1.27 |

*ICRP, 2001

## 2.5 Water Monitoring

DOD installation water supply systems were radiologically monitored by DOD, DOE, and numerous Japanese authorities. Water samples were collected from a variety of sources, including the ocean, surface water bodies, rain water, and household tap water. The purpose of the sampling was multi-fold. The single most important medium for analysis was household tap water, as this may provide a substantial portion of an individual's water intake and exposure from internally-deposited radionuclides. Ocean and surface water body samples aid in the assessment of potential impact to aquatic life, especially if aquatic life is a food source. However, the radioanalysis of aquatic life directly is a more accurate predictor of potential human intake. Analysis of rain water provided an indication of atmospheric radiological contamination and the subsequent deposition on surfaces, but does not have a direct relationship to potential human exposure. Samples from surface water bodies provide an indication of potential human exposure, if the body is a potential source of drinking water. However, due to unknown effects of mixing, decay in transport and storage, and treatment of these sources, measurements at the tap are preferable. In addition, radionuclides in a surface body of water can be a source of external exposure to nearby individuals, but since external exposure is measureable, information on radionuclide concentrations is not useful for assessing these kinds of doses from external sources. Therefore, results for drinking water samples have only been evaluated to assess the suitability of water for consumption and similar uses.

Similar to external dose rate measurements, MEXT analyzed tap water by prefecture daily. Monitoring began in most prefectures by March 18; although for some prefectures, continuity in monitoring was hampered by water service disruptions. For the vast majority of prefectures, radiological contamination from the reactor releases was not detectable in tap water. This was likely the case for one of two reasons. First, many of the prefectures did not have appreciable fallout deposition. As such, surface water sources or recharge zones for groundwater aquifers would not have had any source of contamination. Second, tap water from underground aquifer sources may have low or undetectable concentrations of reactor-based contaminants, even if land areas above the aquifer were impacted by fallout deposition, due to mixing, and delays in the transport of contamination from the surface to the aquifer.

Among the prefectures with tap water impacted by reactor-based contaminants, Ibaraki, Kanagawa, and Tokyo are important to the context of this report because of the USFJ installations located in them. Figure 14 illustrates the variation of I-131 concentrations in the tap water for these three prefectures as reported by MEXT (2011). The concentrations have a general, decreasing trend with distance of the water source from the reactor. None of the tap water samples collected in late April had detectable I-131; a condition that is likely attributable to radioactive decay and dilution of the contaminants in the source. Figure 15 displays concentrations of Cs-137 for Ibaraki and Tokyo Prefectures, while Kanagawa did not have detectable concentrations in any of the samples (MEXT, 2011). It is important to note that most of the laboratories reporting water analysis results commonly listed I-131 and Cs-137, but omitted Cs-134. The Cs-134 activity concentrations were generally equivalent to the Cs-137 in soil and air samples, with a similar relationship in water. Therefore, for internal dosimetry calculations, Cs-134 concentrations were assumed to be equivalent to the Cs-137 in the absence of reported results.

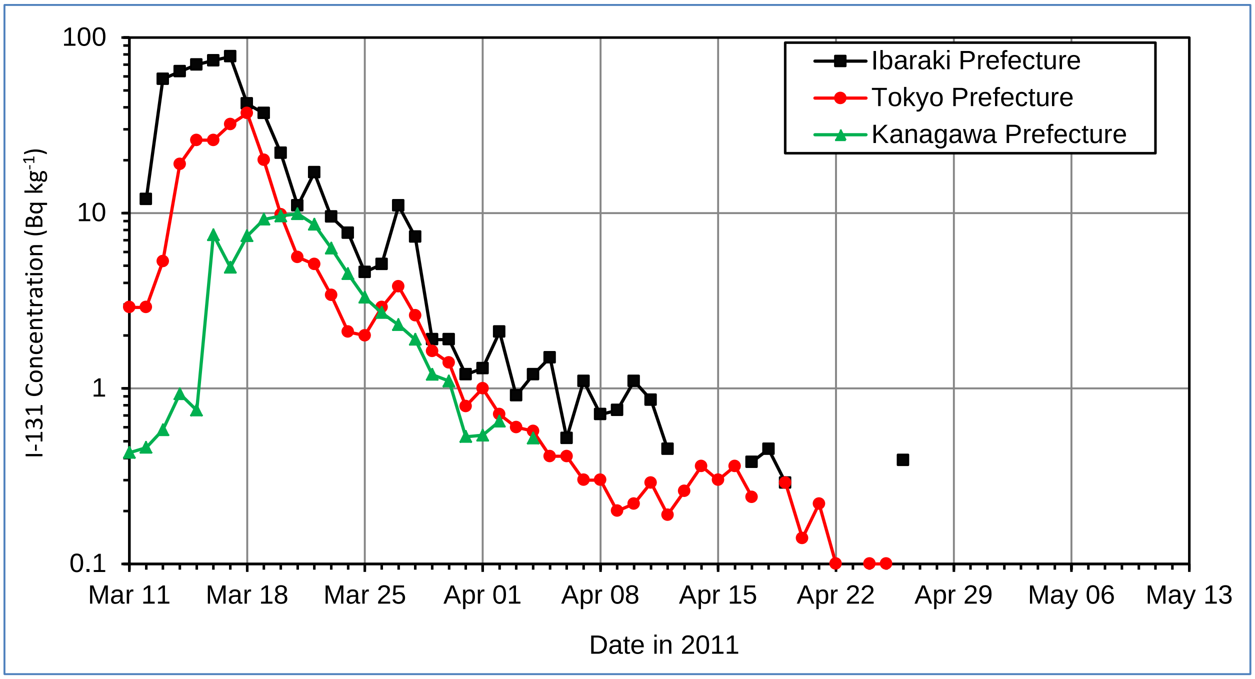


**Figure 14. I-131 concentrations in tap water in Ibaraki, Tokyo, and Kanagawa Prefectures**

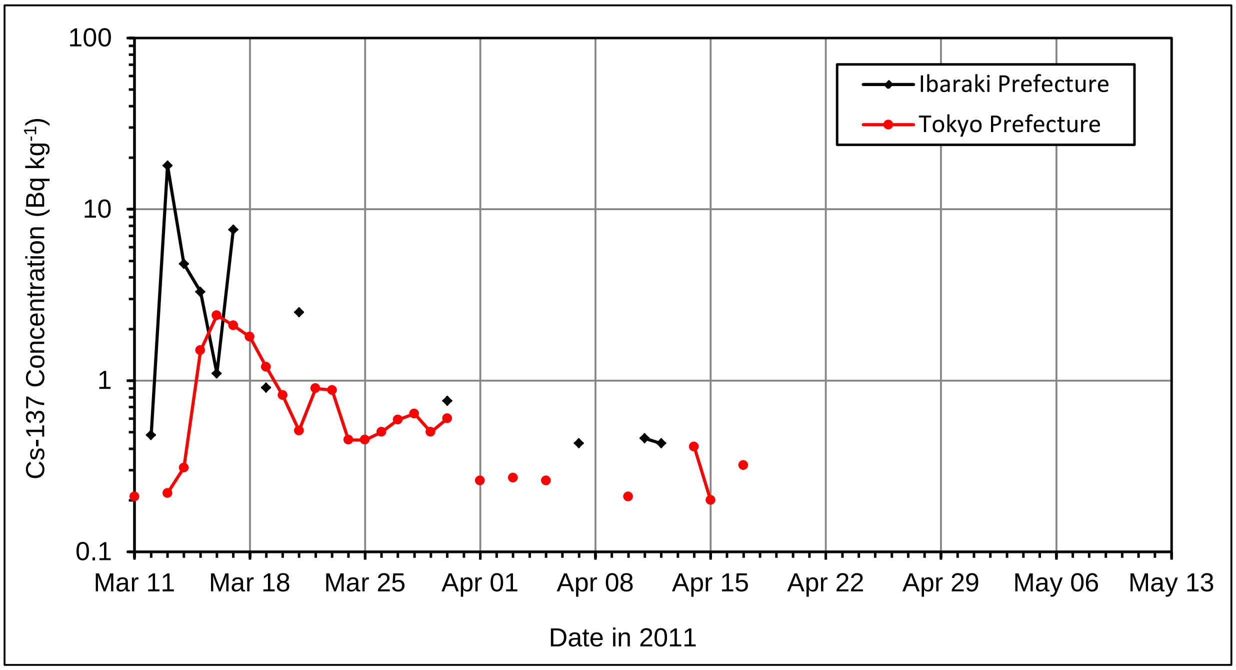


**Figure 15. Cs-137 concentrations in tap water in Ibaraki and Tokyo Prefectures**

USAFSAM analyzed drinking water samples from Yokota AB, Misawa AB, and the USN installation in Kanagawa Prefecture, as well as a small number of samples from other locations in Kanagawa Prefecture and Camp Fuji. The sampling covered only a portion of the

period covered by MEXT water sampling, missing two weeks immediately after the tsunami. Because these samples were sent to USAFSAM's laboratory at Wright-Patterson AFB, OH, the detection sensitivity for I-131 was limited in many of the samples. Table 13 contains maximum concentrations for I-131, Cs-134, and Cs-137 for water samples analyzed by USAFSAM. For Yokota AB, which obtains most of its water from groundwater sources, reported results were less than the water concentration values for Tokyo Prefecture, which were analyzed by MEXT.

**Table 13. Summary of USAFSAM drinking water analyses**

| Installation(s) | Sampling Dates | Number of Samples | Maximum Concentration ($Bq\ kg^{-1}$)* | | |
|---|---|---|---|---|---|
| | | | I-131 | Cs-134 | Cs-137 |
| Yokota AB | Mar 25–Apr 11 | 20 | 0.086 | < 0.12 | 0.073 |
| Misawa AB | Mar 25–Apr 28 | 33 | < 0.28 | < 0.013 | < 0.013 |
| Yokosuka NB | Mar 25–May 2 | 96 | 8.2 | 0.32 | 0.31 |
| Camp Fuji & others in Kanagawa Prefecture | Mar 27–May 2 | 19 | < 15.2 | < 0.40 | < 0.39 |

*Values with "<" are called less-than values and indicate that the results for all measurements made during the sampling date(s) were less than the value indicated.

This was not unexpected because Yokota AB relies predominantly on groundwater sources, while the Tokyo metropolitan area predominantly receives water from surface water (USAFSAM, 2011). The AIPH analyzed drinking water sources for five USA installations in Kanagawa Prefecture between March 20 and May 22, as listed in Table 14. Although the sampling effort was initiated later than the MEXT sampling program, it was accomplished earlier than the sampling and analyses performed by USAFSAM listed in Table 13. Nevertheless, the activity concentrations at both the MEXT and USA installations in Kanagawa Prefecture are low.

Table 15 lists maximum concentrations for water samples analyzed by the USN. Consistent with other drinking water samples collected for installations in Kanagawa Prefecture, the values are low. This table also lists maximum results for non-potable water sources. Among the highest concentrations reported were for seawater and rainwater samples. (AIPH, 2011; MEXT, 2011)

**Table 14. Summary of AIPH drinking water analyses**

| Installation(s) | Sampling Dates | Number of Samples | Maximum Concentration ($Bq\ kg^{-1}$) | | |
|---|---|---|---|---|---|
| | | | I-131 | Cs-134 | Cs-137 |
| Camp Zama | Mar 20–May 22 | 138 | 6.11 | 0.81 | 3.4 |
| Akasaka Press Center | Mar 20–May 22 | 46 | 17.5 | 0.88 | 1.0 |
| Sagama General Depot | Mar 20–May 22 | 49 | 0.91 | 0.33 | 0.36 |
| Sagamihara Housing Area | Mar 20–May 22 | 49 | 0.44 | 0.45 | 0.37 |
| Yokohama North Dock | Mar 20–May 22 | 46 | 6.3 | 0.49 | 0.36 |

**Table 15. Summary of USN water analyses**

| Sampling Points (water type) | Sampling Dates | Number of Samples | Maximum Concentration (Bq kg$^{-1}$) | | |
|---|---|---|---|---|---|
| | | | I-131 | Cs-134 | Cs-137 |
| Naval Ships (potable water) | Mar 29–Apr 24 | 46 | 3.0 | < 0.88 | < 0.93 |
| Yokosuka NB (sea water) | Mar 27–Apr 24 | 41 | 2000 | 222 | 429 |
| Yokosuka NB (fire pump water) | Mar 27–Mar 28 | 3 | < 0.84 | < 0.58 | < 0.67 |
| Atsugi NAF (helicopter washdown) | Apr 9 | 2 | 29 | 7.3 | 8.2 |
| Yokosuka NB (rain) | Mar 22–Apr 11 | 3 | 45 | 27 | 112 |
| USS Ronald Reagan (sea water) | Apr 15 | 6 | 0.56 | 0.59 | 0.69 |
| Yokosuka NB (pure water) | Apr 21–Apr 23 | 5 | 0.50 | 29.5 | 0.68 |

Most individuals assigned and billeted on installations were likely to receive a majority of their drinking water on the base; except for any bottled water consumed. However, individuals and families billeted off-base or involved in off-base activities were likely to consume some water from municipal water supplies. For some of the installations, such as Yokosuka NB, water is supplied by the local municipality. Therefore, to ensure conservative dose estimates from intakes of drinking water, it was assumed: (1) individuals drank tap water not bottled water, and (2) all tap water was derived from surface water sources rather than underground sources, e.g., wells. Because DOD did not sample surface waters, MEXT data for surface water were the only water concentrations used to calculate radiation dose from water intake. This is especially conservative for an installation like Yokota AB, where the assumption is made that the base population consumed water with radioactive material concentrations similar to the Tokyo MEXT station, despite the fact that groundwater sources only were utilized at Yokota AB after the FDNPS accident (AIPH, 2011; MEXT 2011).

## 2.6 Soil Monitoring

Radiological content of soils was assessed by DOD and DOE response teams, and a number of Japanese entities. Compared to the number of radiation dose measurements and air samples conducted by DOD response teams, soil samples were considerably fewer. DOE and GOJ conducted extensive soil sampling, ground-based in-situ measurements with portable spectrometers, and airborne measurements with spectrometers. Most of these measurements were conducted in areas closer to the reactor than those of USFJ installations, and therefore were not applicable to estimates of dose for many DARWG locations. Japanese authorities used this information primarily for the assessment of suitability for future agricultural uses or inhabitance. For this report, the soil data were used in estimating doses from the direct ingestion of soil, which is assumed to be incidental. The soil data could also be useful in predicting external dose

rates; however, due to the collection of external dose measurements and issuance of personal dosimeters, the data were not used for that purpose.

The only soil data used in this report were based on sampling and analysis by the AFRAT and the AIPH. There was variability in the number of samples collected at USFJ installations and in the range of sampling dates. AFRAT soil sampling dates ranged from March 18 to April 24, while AIPH sampling dates ranged from March 28 to April 19. Among the four DARWG locations in the Kanto Plain, the lowest number of samples (six) was collected for the Yokota AB location, while the location encompassing Camp Zama had the highest with 22 samples. Since sampling covered neither the initial contamination density of surface soils on March 11, nor the deposition during April 24 and May 12, some extrapolations of the data were necessary to estimate soil concentrations during this time. Similarly, between dates when samples were collected, it was necessary to interpolate soil concentration data to estimate concentration for days when samples were not collected. Some differences in sampling techniques, which were expected, and anticipated variability in deposition and retention of radionuclides in soils over time contributed to the variations in the results of laboratory analyses of soil samples. Methods used to collect soil samples included: (1) using a soil template (12 cm × 20 cm) and collecting a 5-cm thick sample and (2) samples taken 15 cm deep. It is likely that the tools used to collect the samples also differed among the teams. The differences in method and tools used arose from the tasking received by the sampling teams. Due to these factors, variability was observed in the activity concentration of radionuclides in soil samples collected on the same installation and on the same day.

Table 16 lists soil sampling results for samples collected at Yokota AB and analyzed by the AFRAT field laboratory, which was temporarily deployed to Yokota AB during OT. Analytical values were reported only for radionuclides with concentrations greater than the minimum detectable concentration (MDC). Other radionuclides were detected in samples collected closer to the reactor, for example, at Camp Sendai, Ohanama Port, and others. The data in Table 16 illustrate the variability observed in the soil sample data set as a whole. For example, for the days that had the collection of two samples, significant differences were observed in the activity concentrations of Cs-137. The concentrations differed by a factor of 1.5 for samples collected on April 14 and by a factor 3.5 for the samples collected on April 21. For days with multiple samples, the mean activity concentration among the samples was used as an estimate of soil concentration for that day at a DARWG location.

**Table 16. Reported activity concentrations for soil samples from Yokota AB**

| Sampling Date in 2011 | Activity Concentration (pCi $g^{-1}$) | | | | | Notes |
|---|---|---|---|---|---|---|
| | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 | |
| March 24 | 0.945 | 0.105 | 1.12 | 16.1 | 4.28 | AFRAT Collected, Building 1503 |
| April 8 | 0.36 | -- | 0.401 | 0.829 | -- | AFRAT Collected, Building 1503 |
| April 14 | 1.22 | -- | 1.30 | 1.95 | 0.043 | AFRAT Collected, Building 1556 |
| April 14 | 0.806 | -- | 0.86 | 1.22 | -- | AFRAT Collected, near the dining facility |
| April 21 | 5.63 | 0.165 | 6.73 | 4.81 | -- | AFRAT Collected, Building 1503 |
| April 21 | 1.36 | -- | 1.94 | 1.23 | -- | AFRAT Collected, Building 1503 |

Table 17 lists the estimated soil concentrations for the DARWG location that includes Yokota AB (D-8). The cell entries on the left side of the table are reported activity concentrations of individual soil samples, mean activity concentrations of soil samples for days where multiple samples were collected, or inferred concentrations based on extrapolations or interpolations of sampling data for days without reported concentrations. The non-highlighted cells on the left side of the table are based on sampling data, while the highlighted cells contain inferred values. In the case of this data set, activity concentrations in soils for days preceding March 24 (the first day a soil sample was collected for this location), it was assumed that all of the deposition occurred on March 12 and that environment removal was negligible. With the exception of mechanical disturbance of surface soils by human activities, this is a reasonable assumption for soil samples collected from vegetated areas during this period of time. To support these assumptions, activity concentrations were decayed back in time to March 12. This is a conservative assumption, as the concentrations observed in soils on March 24 are the result of deposition between March 12 and 24. From air sampling data shown above, peak airborne concentrations during this period of time were observed on March 15–16 and March 20–21, with the reasonable assumption that ground deposition followed a similar temporal pattern.

For times between March 24 and April 8, the DARWG decided to radiologically decay the concentration data from the March 24 sample throughout this time period because the Cs-134 and Cs-137 concentrations of the April 8 sample were roughly a factor of three lower than those of the March 24 sample. Furthermore, the mean activity concentrations of Cs-134 and Cs-137 in the two April 14 samples were more than two-fold higher than those of the April 8 sample. It seemed unreasonable to assume that the upper two inches of surface soils had been depleted of Cs-134 and C-137 over this short period of time. The most logical explanation for the disagreement between the cesium activity concentrations of the April 8 sample and that of the March 24 and April 14 samples is variability in sampling and/or soil deposition patterns. Therefore, activity concentrations in soils were radiologically decayed from either the March 24 or April 14 values to cover this period. The pale blue-highlighted cells (light gray in gray scale) have radiological extrapolations backward in time, while the light red-highlighted cells (darker gray in gray scale) have radiological extrapolations forward in time. For this time period, Cs-136 and Te-132 activity concentrations were extrapolated forward in time from the March 24 activity concentration values because their respective concentrations were below the MDC for the April 14 samples. For Cs-134, Cs-137, and I-131, extrapolations were performed from the date that provided the greatest concentrations during this period of time.

For times between April 15 and 23, activity concentrations were extrapolated from mean activity concentrations of the April 24 samples because the mean Cs-134 and Cs-137 activity concentrations in the April 24 samples were higher than the mean of the April 14 samples. This measure effectively assumed that all of the net difference in activity observed in the April 24 samples above the April 14 samples was deposited on April 15. Although this is a conservative assumption, there is no technical foundation for the assumption that the deposition occurred on April 15, or even that there was any substantial deposition during this period of time, because the air sampling data do not indicate any significant depositions during this period of time. For Cs-136 in the April 24 samples, only one sample had a reported concentration, with the other sample having an activity concentration below the MDC. The reported value for April 24 in the table is based on the ratio of Cs-136 to the total Cs-134 and Cs-137 in the sample with a reported Cs-136 concentration, applied to the mean of the total Cs-134 and Cs-137 concentrations for the two samples.

For dates after April 24, activity concentrations in soils were extrapolated from April 24 data, under the assumptions that additional deposition was negligible compared to the activity already accumulated in the soils, and that the only removal process was radioactive decay. For the right portion of Table 17, most of the values were directly transferred from the left portion of the table. For days where the sampling results were not used for extrapolation of activity concentration to other days, activity concentration for these days was based on the mean of the concentrations from the day before and the day after this date. The table makes note of these interpolations. Figure 16 contains a plot of the activity concentrations from the right portion of Table 17. Solid filled markers denoted the dates where soil activity concentrations directly correlate to soil sampling results.

**Table 17. Radionuclide activity concentrations for soil ingestion pathway for Yokota AB**

| Sample Date in 2011 | Sampling Data and Inferred Concentrations | | | | | | Soil Concentrations for Soil Ingestion Pathway | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Activity Concentration (pCi g$^{-1}$) | | | | | Source* | Activity Concentration (pCi g$^{-1}$) | | | | |
| | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 | | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 |
| March 12 | 0.956 | 0.193 | 1.12 | 45.3 | 55.3 | Inferred | 0.956 | 0.193 | 1.12 | 45.3 | 55.3 |
| March 13 | 0.955 | 0.183 | 1.12 | 41.6 | 44.7 | Inferred | 0.955 | 0.183 | 1.12 | 41.6 | 44.7 |
| March 14 | 0.954 | 0.174 | 1.12 | 38.1 | 36.1 | Inferred | 0.954 | 0.174 | 1.12 | 38.1 | 36.1 |
| March 15 | 0.953 | 0.166 | 1.12 | 35 | 29.2 | Inferred | 0.953 | 0.166 | 1.12 | 35 | 29.2 |
| March 16 | 0.952 | 0.157 | 1.12 | 32.1 | 23.6 | Inferred | 0.952 | 0.157 | 1.12 | 32.1 | 23.6 |
| March 17 | 0.951 | 0.15 | 1.12 | 29.4 | 19 | Inferred | 0.951 | 0.15 | 1.12 | 29.4 | 19 |
| March 18 | 0.95 | 0.142 | 1.12 | 27 | 15.4 | Inferred | 0.95 | 0.142 | 1.12 | 27 | 15.4 |
| March 19 | 0.949 | 0.135 | 1.12 | 24.8 | 12.4 | Inferred | 0.949 | 0.135 | 1.12 | 24.8 | 12.4 |
| March 20 | 0.949 | 0.129 | 1.12 | 22.7 | 10 | Inferred | 0.949 | 0.129 | 1.12 | 22.7 | 10 |
| March 21 | 0.948 | 0.122 | 1.12 | 20.9 | 8.11 | Inferred | 0.948 | 0.122 | 1.12 | 20.9 | 8.11 |
| March 22 | 0.947 | 0.116 | 1.12 | 19.1 | 6.56 | Inferred | 0.947 | 0.116 | 1.12 | 19.1 | 6.56 |
| March 23 | 0.946 | 0.11 | 1.12 | 17.5 | 5.3 | Inferred | 0.946 | 0.11 | 1.12 | 17.5 | 5.3 |
| March 24 | 0.945 | 0.105 | 1.12 | 16.1 | 4.28 | Sample | 0.945 | 0.105 | 1.12 | 16.1 | 4.28 |
| March 25 | 0.944 | 0.0998 | 1.12 | 14.8 | 3.46 | Inferred | 0.944 | 0.0998 | 1.12 | 14.8 | 3.46 |
| March 26 | 0.943 | 0.0949 | 1.12 | 13.6 | 2.79 | Inferred | 0.943 | 0.0949 | 1.12 | 13.6 | 2.79 |
| March 27 | 0.942 | 0.0902 | 1.12 | 12.4 | 2.26 | Inferred | 0.942 | 0.0902 | 1.12 | 12.4 | 2.26 |
| March 28 | 0.942 | 0.0858 | 1.12 | 11.4 | 1.82 | Inferred | 0.942 | 0.0858 | 1.12 | 11.4 | 1.82 |
| March 29 | 0.941 | 0.0815 | 1.12 | 10.5 | 1.47 | Inferred | 0.941 | 0.0815 | 1.12 | 10.5 | 1.47 |
| March 30 | 0.94 | 0.0775 | 1.12 | 9.6 | 1.19 | Inferred | 0.94 | 0.0775 | 1.12 | 9.6 | 1.19 |
| March 31 | 0.939 | 0.0737 | 1.12 | 8.81 | 0.962 | Inferred | 0.939 | 0.0737 | 1.12 | 8.81 | 0.962 |
| April 1 | 0.938 | 0.0701 | 1.12 | 8.08 | 0.777 | Inferred | 0.938 | 0.0701 | 1.12 | 8.08 | 0.777 |
| April 2 | 0.937 | 0.0666 | 1.12 | 7.41 | 0.628 | Inferred | 0.937 | 0.0666 | 1.12 | 7.41 | 0.628 |
| April 3 | 0.936 | 0.0633 | 1.12 | 6.8 | 0.507 | Inferred | 0.936 | 0.0633 | 1.12 | 6.8 | 0.507 |
| April 4 | 0.935 | 0.0602 | 1.12 | 6.24 | 0.41 | Inferred | 0.935 | 0.0602 | 1.12 | 6.24 | 0.41 |
| April 5 | 0.935 | 0.0572 | 1.12 | 5.72 | 0.331 | Inferred | 0.935 | 0.0572 | 1.12 | 5.72 | 0.331 |
| April 6 | 0.934 | 0.0544 | 1.12 | 5.25 | 0.268 | Inferred | 0.934 | 0.0544 | 1.12 | 5.25 | 0.268 |
| April 7 | 0.933 | 0.0517 | 1.12 | 4.82 | 0.216 | Inferred | 0.933 | 0.0517 | 1.12 | 4.82 | 0.216 |
| April 8 | 0.36 | 0.0492 | 0.401 | 0.829 | 0.175 | Sample | 0.977† | 0.0492 | 1.12† | 4.44† | 0.175 |
| April 9 | 1.02 | 0.0467 | 1.12 | 4.05 | 0.141 | Inferred | 1.02 | 0.0467 | 1.12 | 4.05 | 0.141 |
| April 10 | 1.02 | 0.0444 | 1.12 | 3.72 | 0.114 | Inferred | 1.02 | 0.0444 | 1.12 | 3.72 | 0.114 |

Legend: [blue] Extrapolated backward in time. [orange] Extrapolated forward in time.

*Source of concentration is sample or inferred

†Mean of concentration of day before and day after

‡Mean value of two samples at Yokota AB

§Value obtained from subject matter expert interpretation as discussed in text.

**Table 17. Radionuclide activity concentrations for soil ingestion pathway for Yokota AB (D-8) (cont.)**

| Sample Date in 2011 | Sampling Data and Inferred Concentrations | | | | | | Soil Concentrations for Soil Ingestion Pathway | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Activity Concentration (pCi $g^{-1}$) | | | | | Source* | Activity Concentration (pCi $g^{-1}$) | | | | |
| | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 | | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 |
| April 11 | 1.02 | 0.0422 | 1.12 | 3.41 | 0.0922 | Inferred | 1.02 | 0.0422 | 1.12 | 3.41 | 0.0922 |
| April 12 | 1.02 | 0.0402 | 1.12 | 3.13 | 0.0745 | Inferred | 1.02 | 0.0402 | 1.12 | 3.13 | 0.0745 |
| April 13 | 1.02 | 0.0382 | 1.12 | 2.87 | 0.0602 | Inferred | 1.02 | 0.0382 | 1.12 | 2.87 | 0.0602 |
| April 14 | 1.02‡ | 0.173 | 1.08‡ | 1.58‡ | 0.0486 | Samples | 2.27† | 0.173 | 2.73† | 4.72† | 0.0486 |
| April 15 | 3.52 | 0.165 | 4.34 | 6.56 | 0.0393 | Inferred | 3.52 | 0.165 | 4.34 | 6.56 | 0.0393 |
| April 16 | 3.52 | 0.156 | 4.34 | 6.02 | 0.0317 | Inferred | 3.52 | 0.156 | 4.34 | 6.02 | 0.0317 |
| April 17 | 3.52 | 0.149 | 4.34 | 5.52 | 0.0256 | Inferred | 3.52 | 0.149 | 4.34 | 5.52 | 0.0256 |
| April 18 | 3.51 | 0.141 | 4.34 | 5.07 | 0.0207 | Inferred | 3.51 | 0.141 | 4.34 | 5.07 | 0.0207 |
| April 19 | 3.51 | 0.134 | 4.34 | 4.65 | 0.0167 | Inferred | 3.51 | 0.134 | 4.34 | 4.65 | 0.0167 |
| April 20 | 3.51 | 0.128 | 4.34 | 4.26 | 0.0135 | Inferred | 3.51 | 0.128 | 4.34 | 4.26 | 0.0135 |
| April 21 | 3.5 | 0.122 | 4.34 | 3.91 | 0.0109 | Inferred | 3.5 | 0.122 | 4.34 | 3.91 | 0.0109 |
| April 22 | 3.5 | 0.116 | 4.34 | 3.59 | 0.0088 | Inferred | 3.5 | 0.116 | 4.34 | 3.59 | 0.0088 |
| April 23 | 3.5 | 0.11 | 4.34 | 3.29 | 0.0071 | Inferred | 3.5 | 0.11 | 4.34 | 3.29 | 0.0071 |
| April 24 | 3.5‡ | 0.104§ | 4.34‡ | 3.02‡ | 0.0058 | Samples | 3.5 | 0.104 | 4.34 | 3.02 | 0.0058 |
| April 25 | 3.49 | 0.0993 | 4.33 | 2.77 | 0.0047 | Inferred | 3.49 | 0.0993 | 4.33 | 2.77 | 0.0047 |
| April 26 | 3.49 | 0.0944 | 4.33 | 2.54 | 0.0038 | Inferred | 3.49 | 0.0944 | 4.33 | 2.54 | 0.0038 |
| April 27 | 3.49 | 0.0897 | 4.33 | 2.33 | 0.0030 | Inferred | 3.49 | 0.0897 | 4.33 | 2.33 | 0.0030 |
| April 28 | 3.48 | 0.0853 | 4.33 | 2.14 | 0.0025 | Inferred | 3.48 | 0.0853 | 4.33 | 2.14 | 0.0025 |
| April 29 | 3.48 | 0.0811 | 4.33 | 1.96 | 0.0020 | Inferred | 3.48 | 0.0811 | 4.33 | 1.96 | 0.0020 |
| April 30 | 3.48 | 0.0771 | 4.33 | 1.8 | 0.0016 | Inferred | 3.48 | 0.0771 | 4.33 | 1.8 | 0.0016 |
| May1 | 3.47 | 0.0733 | 4.33 | 1.65 | 0.0013 | Inferred | 3.47 | 0.0733 | 4.33 | 1.65 | 0.0013 |
| May2 | 3.47 | 0.0697 | 4.33 | 1.52 | 0.0011 | Inferred | 3.47 | 0.0697 | 4.33 | 1.52 | 0.0011 |
| May3 | 3.47 | 0.0662 | 4.33 | 1.39 | 0.0008 | Inferred | 3.47 | 0.0662 | 4.33 | 1.39 | 0.0008 |
| May4 | 3.46 | 0.063 | 4.33 | 1.28 | 0.0007 | Inferred | 3.46 | 0.063 | 4.33 | 1.28 | 0.0007 |
| May5 | 3.46 | 0.0598 | 4.33 | 1.17 | 0.0006 | Inferred | 3.46 | 0.0598 | 4.33 | 1.17 | 0.0006 |
| May6 | 3.46 | 0.0569 | 4.33 | 1.07 | 0.0004 | Inferred | 3.46 | 0.0569 | 4.33 | 1.07 | 0.0004 |
| May7 | 3.45 | 0.0541 | 4.33 | 0.985 | 0.0004 | Inferred | 3.45 | 0.0541 | 4.33 | 0.985 | 0.0004 |
| May8 | 3.45 | 0.0514 | 4.33 | 0.904 | 0.0003 | Inferred | 3.45 | 0.0514 | 4.33 | 0.904 | 0.0003 |
| May9 | 3.45 | 0.0489 | 4.33 | 0.829 | 0.0002 | Inferred | 3.45 | 0.0489 | 4.33 | 0.829 | 0.0002 |
| May10 | 3.44 | 0.0465 | 4.33 | 0.76 | 0.0002 | Inferred | 3.44 | 0.0465 | 4.33 | 0.76 | 0.0002 |
| May11 | 3.44 | 0.0442 | 4.33 | 0.698 | 0.0002 | Inferred | 3.44 | 0.0442 | 4.33 | 0.698 | 0.0002 |

Legend: [blue] Extrapolated backward in time. [orange] Extrapolated forward in time.

*Source of concentration is sample or inferred

†Mean of concentration of day before and day after

‡Mean value of two samples at Yokota AB

§Value obtained from subject matter expert interpretation as discussed in text.

Table 18 lists the soil sampling data for the DARWG location (D-10) that includes Camp Zama and Atsugi NAF. The dates of sampling range from March 18 to April 18, although all but three samples were collected on April 18. For this data set, extrapolation of soil activity concentrations for March 11–17 was based on the March 18 sample results for Cs-134 and Cs-137, but not Te-132 or Cs-136 since they were only detected in the samples collected on April 1 samples and in the one sample collected on April 18. While I-131 was detected in this sample, the activity concentration was much lower in proportion to the Cs-137 than was observed in the soil sample from the other consolidated locations in the Kanto Plain and the Yokota AB high volume air sampling for this day.

For times after March 18, the activity concentrations of all cesium isotopes were based on mean concentrations of soils collected on April 18 or extrapolations from this date. While it seemed unreasonable for significant loss of long-lived radionuclides from surface soils over short time periods, it seemed imprudent to extrapolate March 18 activity concentrations beyond March 18. This conclusion was due in part to the large number of samples collected on April 18, although the mean Cs-134 and Cs-137 activity concentrations of those samples were about half of those in the March 18 sample. Iodine-131 activity concentrations were based on the mean concentration in the April 18 samples and extrapolations from this date assumed radiological decay alone. Tellurium-132 was handled in a similar manner based on the Te-132 measurement on April 1, but scaled higher by a factor of 12.7 from the actual measured value. The factor was based on the ratio of estimated I-131 for this day to that measured in the sample. The scaling of tellurium to an iodine isotope was considered appropriate due to the similar anticipated release rates from reactors. The plot of estimated soil concentrations for the Atsugi NAF (D-10) is in Figure 17. Similar to Figure 16, the solid-filled markers denote dates where soil activity concentrations directly correlate to soil sampling results. Similar methods were used for evaluation of data for the DARWG locations that contain Akasaka Press Center (D-9) and Yokosuka NB (D-11). Data summary tables and plots are not contained here. Table 19 contains the estimated mean activity concentrations for the DARWG locations (D-8, D-9, D-10, and D-11) in the Kanto Plain, during the period March 12 to May 11. Despite limited soil sampling data over this period of time and the expected variability, there was reasonably good agreement in mean concentrations among the locations, with the exception of the estimated Cs-134 and Cs-137 concentrations for Akasaka Press Center (D-9), which were less than half of the estimated concentrations for the other three locations. Overall, however, a number of conservative assumptions were made in the evaluation of data for each location.

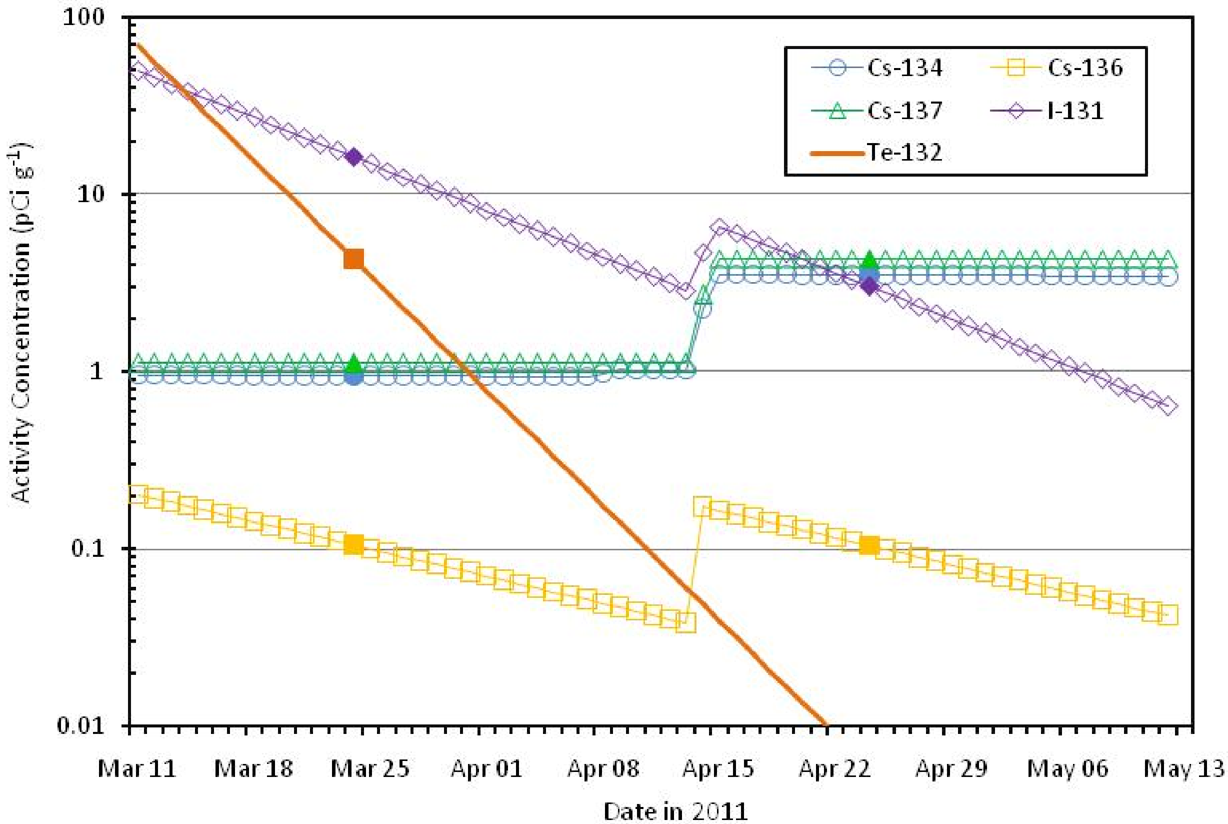


**Figure 16. Estimated soil concentrations for Yokota AB**

**Table 18. Reported activity concentrations for soil samples from Camp Zama and Atsugi NAF**

| Sampling Date in 2011 | Activity Concentration (pCi $g^{-1}$) | | | | | Notes |
|---|---|---|---|---|---|---|
| | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 | |
| March 18 | 3.025 | | 3.75 | 2.04 | | AFRAT Collected, Sagama Depot |
| April 01 | 0.0407 | | 0.0624 | 0.526 | 0.024 | AFRAT Collected, Atsugi NAF |
| April 11 | 0.21 | | 0.27 | 1.43 | | AFRAT Collected, Atsugi NAF |
| April 18 | 0.219 | | 0.281 | 1.044 | | AFRAT Collected, Atsugi NAF |
| April 18 | 2.4 | | 2.87 | 1.47 | | AFRAT Collected, Sagama Depot |
| April 18 | 0.953 | | 0.9925 | 0.811 | | AFRAT Collected, Sagamihara |
| April 18 | 3.29 | | 3.87 | 2.51 | | AFRAT Collected, Sagama Depot |
| April 18 | 1.14 | | 1.18 | 0.92 | | AFRAT Collected, Sagamihara |
| April 18 | 0.647 | | 0.9385 | 0.593 | | AFRAT Collected at Sagamihara Housing Area |
| April 18 | 1.07 | | 1.25 | 1.075 | | AFRAT Collected at Camp Zama |
| April 18 | 1.66 | | 1.825 | 4.38 | | AFRAT Collected at Camp Zama (High Traffic Area) |
| April 18 | 5.81 | 0.173 | 6.59 | 3.5 | | AFRAT Collected, Sagamihara |
| April 18 | 1.345 | | 1.495 | 1.47 | | AFRAT Collected, Sagamihara |
| April 18 | 1.8 | | 2.2 | 2.2 | | AIPH Collected, Camp Zama (High Elevation Area) |
| April 18 | 0.39 | | 0.51 | 0.74 | | AIPH Collected, Camp Zama (High Traffic Area) |
| April 18 | 0.47 | | 0.74 | 0.47 | | AIPH Collected, Camp Zama (Runoff Area) |
| April 18 | 1.1 | | 1.3 | 1.5 | | AIPH Collected, Sagama (High Elevation Area) |
| April 18 | 0.71 | | 1.4 | 0.43 | | AIPH Collected, Sagama (High Traffic Area) |
| April 18 | 2.3 | | 3.2 | 2.1 | | AIPH Collected, Sagama (Runoff Area) |
| April 18 | 0.94 | | 1.2 | 1.3 | | AIPH Collected, Sagamihara (High Elevation Area) |
| April 18 | 1.4 | | 1.7 | 1 | | AIPH Collected, Sagamihara (High Traffic Area) |
| April 18 | 1.3 | | 1.8 | 1.1 | | AIPH Collected, Sagamihara (Runoff Area) |

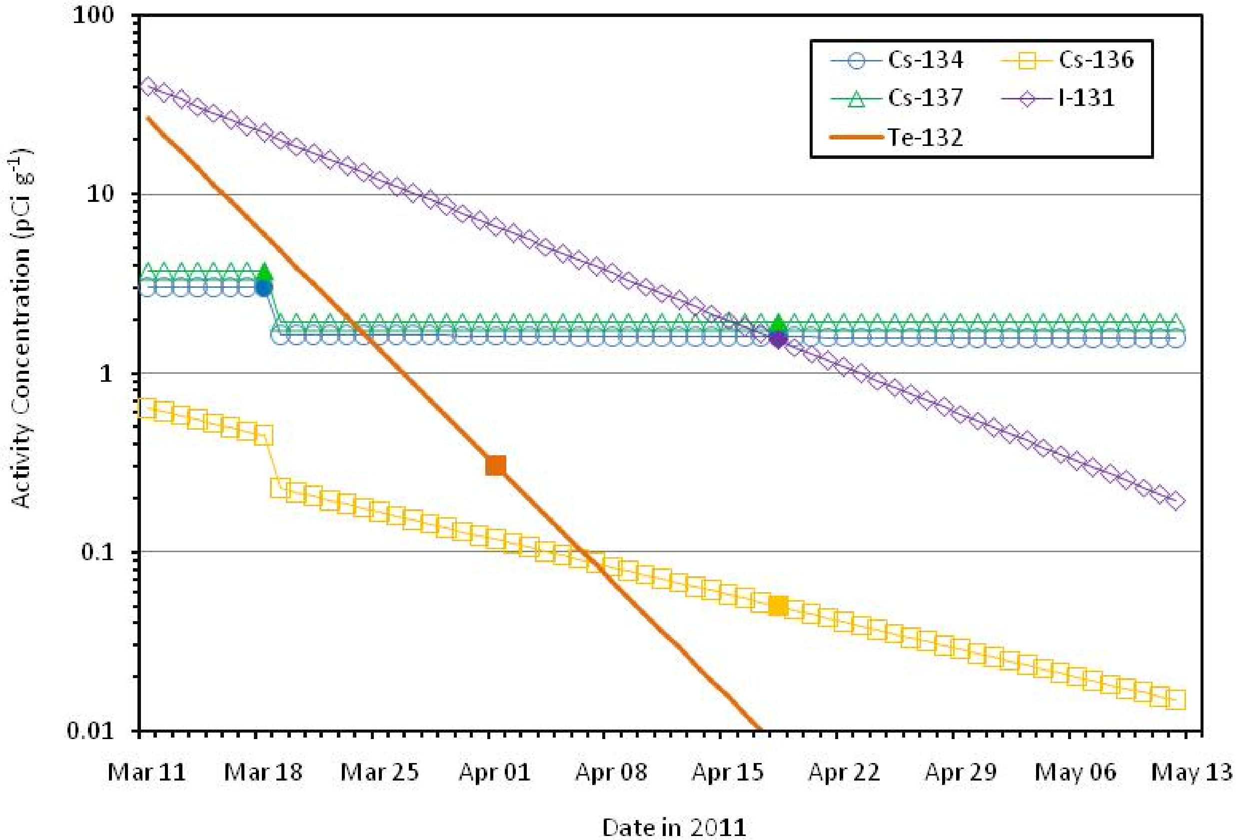


**Figure 17. Estimated soil concentrations for soil samples from Camp Zama and Atsugi NAF**

**Table 19. Mean estimated surface soil concentrations for DARWG Locations in the Kanto Plain for March 12 through May 11**

| DARWG Location | Activity Concentration (pCi $g^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Cs-134 | Cs-136 | Cs-137 | I-131 | Te-132 |
| Yokota AB (D-8) | 2.10 | 0.10 | 2.57 | 10.21 | 5.66 |
| Akasaka Press Center (D-9) | 0.74 | 0.11 | 0.88 | 6.04 | 2.15 |
| Atsugi NAF (D-10) | 1.78 | 0.14 | 2.18 | 7.76 | 2.21 |
| Yokosuka NB (D-11) | 2.00 | 0.19 | 2.4 | 8.96 | 2.70 |

## 2.7 Food Monitoring

### 2.7.1. Introduction

The damage from the earthquake and subsequent tsunami concentrated in the northern parts of the country (mainly Hokkaido and Honshu); much of the agricultural and fishing facilities in Japan were devastated (Nanto, 2011). Figure 18 illustrates the extent of the damage caused to fisheries by the earthquake and tsunami (Nanto, 2011). Japan's Ministry of Agriculture, Forestry,

and Fisheries (MAFF) maintains a website documenting the damage from and response to the earthquake including the accident at the FDNPS (MAFF, 2012). The most recent information from MAFF (2012) indicates that over 25,000 fishing vessels, 319 fishery harbor facilities, and 1725 common use fishery facilities sustained about one trillion Japanese yen (JPY) (about $800 billion U.S. dollars[7] [USD]) in damage. This does not include damage to aquaculture products and facilities whose damage totaled about 130 billion JPY (about $100 billion USD). Agricultural damage information from MAFF (2012) indicates roughly 800 billion JPY (about $600 billion USD) damage to about 39,000 "points[8]."

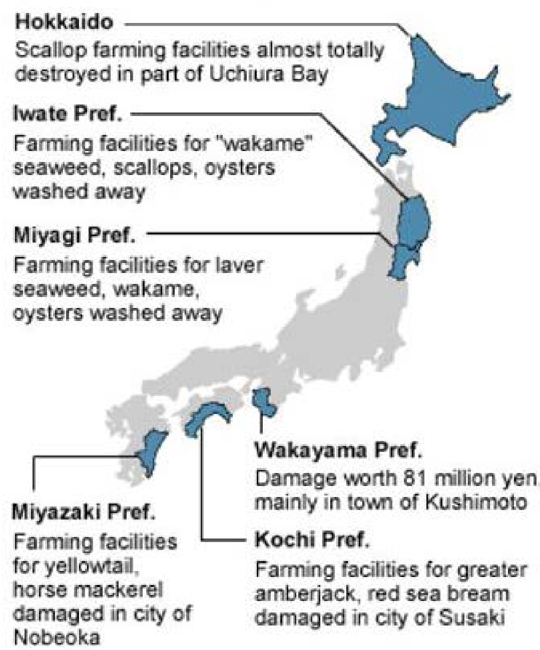


**Figure 18. Tsunami damage to Japanese aquaculture**

The releases of radioactive material from the FDNPS were widespread and are discussed previously in this section. As of February 2, 2012, the Japanese Ministry of Health, Labor and Welfare analyzed 102,271 foodstuff samples (collection started March 19, 2011); 1106 samples exceeded GOJ action levels[9] (See Table 20 below for the action levels.)

[7] Exchange rate of about $0.75 to the Japanese yen. Source: http://www.boj.or.jp/en/statistics/market/forex/fxdaily/index.htm/, accessed February 5, 2012.)
[8] "Points" is term used on the web site at http://www.maff.go.jp/e/quake/press_since_120605.html to describe agricultural locations.
[9] (Source: http://www.mhlw.go.jp/english/topics/2011eq/dl/02Feb2012_Sum_up.pdf, accessed February 5, 2012.)

### 2.7.2. DOD Food Procurement, Distribution, and Safety

According to Mara, A. and McGrath, L. (2009) of the National Defense University, "The U.S. military receives food through a long and complex system." Under 10 USC 2533a (the Berry Amendment), DOD is required to "give preference to the procurement of domestically produced, manufactured, or home grown products, notably food, clothing, fabric, and specialty metals." (Grasso, 2008) DOD implements the Berry Amendment (and exceptions as allowed by law) through the Defense Federal Acquisition Regulations Supplement (DFARS), Part 225.7002. Exceptions to the Berry Amendment are listed in the DFARS section 225.7002-2[10] and include:

- Acquisitions of any of the items in [DFARS section] 225.7002-1, if the Secretary concerned determines that items grown, reprocessed, reused, or produced in the United States cannot be acquired as and when needed in a satisfactory quality and sufficient quantity at U.S. market prices.
- Acquisitions of foods manufactured or processed in the United States, regardless of where the foods (and any component if applicable) were grown or produced. However, in accordance with Section 8118 of the DOD Appropriations Act for Fiscal Year 2005 ([Public Law] 108-287), this exception does not apply to fish, shellfish, or seafood manufactured or processed in the United States or fish, shellfish, or seafood contained in foods manufactured or processed in the United States.
- Acquisitions of perishable foods by or for activities located outside the United States for personnel of those activities.
- Acquisitions of food or hand or measuring tools—
  - In support of contingency operations; or
  - For which the use of other than competitive procedures has been approved on the basis of unusual and compelling urgency in accordance with Federal Acquisition Regulation 6.302-2.
- Emergency acquisitions by activities located outside the United States for personnel of those activities.
- Acquisitions by vessels in foreign waters.
- Acquisitions of items specifically for commissary resale.

The Defense Logistics Agency (DLA), Subsistence Directorate is responsible for procuring and distributing food throughout DOD (DLA, 2011). The Defense Logistics Agency Troop Support, or DLA Troop Support, (formerly, Defense Supply Center Philadelphia) distributes most non-perishable and packaged food for DOD (Mara, A. ; McGrath, L., 2009). The DLA distribution network includes the Defense Commissary Agency (DeCA) whose mission includes "the resale of groceries and related household items." (DOD, 2008) DeCA does not operate mess halls, dining halls, or galleys, nor does DeCA operate clubs, ship stores or other military resale or retail activity (DeCA, 2009). The Food Safety Office of the DLA Subsistence Directorate is responsible for all "food safety issues, All Food and Drug Act (ALFOODACT) system messages, and technical and quality assurance policies for food worldwide." (DLA,

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[10] (http://www.acq.osd.mil/dpap//dars/dfars/html/current/225_70.htm#225.7002, accessed 11 Feb 2012.)

2011) The Japan District Veterinary Command (JDVC), a subordinate command of the USA, Japan, is tasked with DOD food inspection in Japan. It has offices at Misawa AB, Yokota AB, Camp Zama, Yokosuka NB, Iwakuni MCAS, Sasebo NB, and on Okinawa.

#### *2.7.2.1 ALFOODACT 004-2001*

DOD's ALFOODACT system is part of the Federal Government's hazardous food and non-prescription drug recall program. Its intent is to provide worldwide distribution of FDA, U.S. Department of Agriculture, U.S. Department of Commerce, Defense Logistics Agency Troop Support, or other Government or non-Government agency recalls of suspect material in military accounts.

Due to the public health concerns associated with radiation and radioactive contamination, FDA increased surveillance of Japan's regulated products. In response to detection (by the GOJ) of radioactive contamination on certain foodstuffs in Japan, the FDA issued Import Alert 99-33 on March 22, 2011 (FDA, 2011a; 2011b) granting FDA district permission to "detain, without physical examination [DWPE], the specified products from firms" specified prefectures. On March 25, 2011 an update to the import alert specified the Fukushima, Ibaraki, Tochigi, and Gunma prefectures for restriction. In addition, the widespread damage to farms, food production and storage facilities, and general infrastructure caused an increased concern about microbial contamination. In response to these concerns, DOD issued the ALFOODACT 004-2011 on April 1, 2011 (ASD(HA), 2011c; DOD, 2011).

The ALFOODACT 004-2011 was issued to ensure that radioactive contaminated food and bottled water did not reach U.S. Service members or their family members. The issuance resulted in enhanced assessment (testing, verification, and validation) of food production facilities. The ALFOODACT 004-2011,

> suspend[ed] procurement of bottled water (except as noted below for bottled water) and all subsistence items grown in or produced from food sources located in the following prefectures in the Tohoku, Kanto, and Chubu Regions. Specifically, Aomori, Iwate, Miyagi, Akita, Yamagata, and Fukushima prefectures in the Tohoku Region; Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, and Kanagawa prefectures in the Kanto Plain; and Niigata, Nagano, Yamanashi, and Toyama prefectures in the Chubu Region, are included in this suspension of food and bottled water (except as noted below for bottled water) (DOD, 2011).

Products procured prior to April 1, 2011 were not recalled due to the DWPE activities described in Import Alert 99-33.

With respect to bottled water, the ALFOODACT 004-2011 stated that,

> The USA Veterinary Command has evaluated bottled water plants in the identified prefectures and validated that all plants, with the exception of the Daiohs Services Water Plant (previously suspended due to earthquake damage), have sufficient safety measures and testing capabilities to ensure radiation contaminated water does not reach U.S. Forces Japan. Procurement from bottled

water plants may continue with the exception of Daiohs, which is suspended (DOD, 2011).

An update to ALFOODACT 004-2011 was issued on August 7, 2011 (ALFOODACT 010-2011). This update provided a webpage listing establishments in the Japan Suspension Zone that had completed enhanced testing, verification, and validation of food production facilities: www.troopsupport.dla.mil/subs/fso/alfood/japanlist.asp (accessed February 6, 2012).

### *2.7.2.2 Food Safety Response*

Increased surveillance of DOD retail food and food support facilities and food products was implemented at several points of the distribution channel: (1) to ensure timely detection of comingling of contaminated products into shipments, and (2) to establish a collaborative food matrix testing to identify potential contamination that might accumulate into the food or contaminate food during production.

For surface contamination measurements, the radiological action limit used by DOD audit teams for monitoring of food surfaces was two times background. Any reading that exceeded the limits would require immediate notification of the designated health physicist and JDVC Commander. The JDVC Commander was responsible for reviewing all laboratory-testing results and initiating an immediate local hold on the questionable item pending further investigation.

DOD contamination surveys (outside/inside of selected facilities) were initially performed using RadEyes. The teams' capabilities were gradually increased with additional RadEyes and AN/PDR-77s (see Appendix A) with assorted probes. The teams used the RadEye for external exposure rate and surface contamination surveys. The RadEye was the preferred instrument during audits because of weight, transportation and mobility through the plants. The AN/PDR-77 is generally the instrument of choice for laboratory receipt surveillance for all food product surfaces before and after packaging is removed.

A typical external exposure rate measurement was conducted three feet above the ground with the probe held out at arm's length. The surveyor walked slowly through a facility, stopped at a particular location for a minimum of two minutes, and recorded the highest reading.

The AN/PDR-77 with pancake probe was the primary instrument used to assess individual food products. The pancake probe was held about one inch from the case of exposed food products for at least one minute. Food assessment priorities were (1) exposed unpackaged foods, (2) permeable/semi-permeable packaging, and (3) impermeable packaging.

### *2.7.2.3 Laboratory testing*

Routine audits typically assessed and reviewed approved sources who supplied water and food products for consumption by DOD-affiliated individuals by collecting samples of raw ingredients for radiological and bioluminescent surveillance. Samples were typically processed at the Camp Zama Surveillance Laboratory or submitted to another laboratory in the continental United States (CONUS), such as the AIPH, the DOD Veterinary Food Analysis and Diagnostic

Laboratory (FADL) at Fort Sam Houston, TX, or a FDA laboratory. Laboratory testing consisted of food surface and matrix radiological testing, microbiological analysis, and chemical analysis as appropriate. Random samples of the final approved water production sources, which include bottled water plants, were collected for microbiological, chemical, and radiological analysis. Results of testing were then compared with standards for activity in food and water (Table 20).

**Table 20. Food and water activity concentration standards and guidelines (Bq $kg^{-1}$)**

| Nuclide | Item | Japan Provisional Standard* | VETCOM Circular 40-1, Appendix O† | WHO Codex Guideline Levels‡ |
|---|---|---|---|---|
| Iodine (I-131) | Water, Milk, Dairy Products | 300 | 170 | 100 |
| | Vegetables (excluding root crops, potatoes) | 2,000 | | |
| Cesium | Water, Milk, Dairy Products | 200 | 1,200 | 1,000 |
| | Vegetables, Grains, Meats, Fish, and Eggs | 500 | | |

*The Japanese provisional standards are based on an effective dose of 0.5 rem (5 mSv) (GOJ, 2011c). Additionally, according to the WHO, the 300 Bq $kg^{-1}$ standard is based on about an "equivalent annual dose" of 0.25 rem (2.5 mSv) $y^{-1}$, but this content was superseded (WHO, 2011).
†The values used in VETCOM Circular 40-1 (USA, 2012) are based on the FDA DILs of 0.5 rem (5 mSv) committed effective dose equivalent or 5 rem (50 mSv) committed dose equivalent to the individual tissues or organs, whichever is more limiting based on DCs from ICRP-56 (ICRP, 1989). See FDA's 1998 Guidance Levels for Radionuclide Activity Concentration in Food Contained in the CPG [Compliance Policy Guide] for more details (FDA, 1998).
‡The Codex/WHO guideline levels are based on a committed effective dose of 0.1 rem (1 mSv) (WHO, 2009).
Note: All of the standards and guidelines are based on assumptions about the quantity of food and water ingested in a year. Therefore, the dose bases are the radiation doses that would be received from ingesting food or water containing radionuclides at the standard or guideline value for an entire year.

Samples (674 in total) collected in Japan between March 29 and May 12, 2011 of food bound for use or consumption in the United States were analyzed at the FDA's Winchester Engineering Analytical Center (WEAC) for the presence of radioactive contamination by γ-spectrometry. The laboratory's conclusion for all the samples was that "No gamma-ray emitting radionuclides detected" with the occasional exception noted for naturally occurring potassium-40 (K-40). The WEAC reported a minimum detectable concentration (MDC) for I-131 and Cs-137 for each sample. For this set of 674 samples the maximum reported MDCs were 38 Bq $kg^{-1}$ for Cs-137 and 30 Bq $kg^{-1}$ for I-131. Twenty (20) food samples collected by DOD between May 2 and May 12, 2011 were analyzed at the WEAC. Again, the laboratory concluded that for all the samples "No gamma-ray emitting radionuclides [were] detected" with the occasional exception noted for naturally occurring K-40. For this set of 20 samples the maximum reported MDCs were 8 Bq $kg^{-1}$ for Cs-137 and 7 Bq $kg^{-1}$ for I-131.

### 2.7.2.4 World Health Organization Preliminary Dose Estimations

In its 2012 report, WHO evaluated potential radiation doses from external and internal radiation exposure for one year after the FDNPS for people living in the Fukushima prefecture (P-7), prefectures neighboring Fukushima (Miyagi [P-4], Ibaraki [P-8], Tochigi [P-9], Gunma [P-10], and Chiba [P-12]), the "Rest of Japan," nearby countries, and "rest of the world." (WHO, 2012) The prefecture numbers use the numbering scheme shown in Figure 1. Table 21 shows a summary of the population data for the shore-based members of the POI. Other than a few isolated instances of personnel entering J-Village or Camp Sendai at the Sendai Airport (Miyagi, [P-4]), most people were in locations that correspond to the "Rest of Japan" in WHO (2012).

**Table 21. Summary of shore-based population and locations**

| DARWG No.* | Shore Location | Prefecture, No. | Total People |
|---|---|---|---|
| D-1 | Misawa AB | Aomori, P-2 | 8,368 |
| D-8 | Yokota AB | Tokyo, P-13 | 7,907 |
| D-9 | Akasaka Press Center | Tokyo, P-13 | 25 |
| D-10 | Atsugi NAF | Kanagawa, P-14 | 9,039 |
| D-11 | Yokosuka NB | Kanagawa, P-14 | 16,449 |
| D-12 | Camp Fuji | Shizouka, P-22 | 160 |
| D-13 | Iwakuni MCAS | Yamaguchi, P-35 | 5,402 |
| D-14 | Sasebo NB | Nagasaki, P-42 | 5956 |
| | | Total | 53,306 |

*DARWG locations D-2 through D-7 are not listed because significant numbers of DOD-affiliated individuals did not reside in them.

WHO (2012) found that for adults, children (aged 10 years), and infants (aged 1 year) in the "Rest of Japan", the effective dose[11] in the first year after the accident fell in to a band of 0.01 to 0.1 rem (0.1 to 1 mSv). It was also reported that 70 to 80 percent of the radiation dose was from ingestion. Similarly, the thyroid dose band was 0.1 to 1 rem (1 to 10 mSv) with 90 to 100 percent from ingestion (excluding the consumption of tap water, whose dose contribution was "low in comparison with dose from other pathways" [WHO, 2012]). In those locations where food wasn't monitored, WHO (2012) stated that because it assumed that all food consumed came from Fukushima and neighboring prefectures, the radiation doses are "clearly overestimated" DARWG's comparative analysis of the WHO report and this report provides additional details about the similarities and differences in the two approaches and results (Chehata, 2012).

An examination of the radioanalytical data on food from "all prefectures" in the WHO report shows that most of the dose from food consumption was acquired in the first two months (WHO, 2012). To calculate the doses from ingestion intakes, WHO (2012) used the 97.5$^{th}$ percentile value of ingestion rates for the Japanese population combined with the median values of the I-131, Cs-134, and Cs-137 concentrations in food. For preliminary, comparative

[11] The doses reported in WHO (2012) accounted for uncertainties using an approach that did not include the DARWG's assumed factor of 3.

calculations, the DARWG used the 95$^{th}$ percentile values for both the body mass and intake rate as function of body mass as listed in the EPA (2011) because the 97.5$^{th}$ percentile values for daily, population-averaged ingestion rates were unavailable. The DARWG also applied an assumed uncertainty factor of three to the DCs for ingestion used in the calculations. The results of the DARWG's preliminary calculations under these assumptions are shown in Table 22.

**Table 22. Average daily dose rate from ingestion of food from non-DOD sources during the first month after the accident**

| ICRP Age | Committed Effective Dose Rate | | Thyroid Dose Rate | |
|---|---|---|---|---|
| | rem $d^{-1}$ | mSv $d^{-1}$ | rem $d^{-1}$ | mSv $d^{-1}$ |
| 1 y | 0.0034 | 0.034 | 0.064 | 0.64 |
| 10 y | 0.0018 | 0.018 | 0.029 | 0.29 |
| Adult | 0.0014 | 0.014 | 0.016 | 0.16 |

For illustrative purposes, eating on the local economy one day per week for the first month (a total of 4 days), the highest doses would have been calculated for a 1-year old child yielding values of 0.014 rem (0.14 mSv) effective dose and 0.26 rem (2.6 mSv) thyroid dose. Radiation doses for children of other ages and adults would be lower.

Radiation dose estimates to people who were living solely on the local economy near U.S. military installations should be comparable to the values in WHO (2012). Although it is very unlikely that any DOD individual would fit into this category, comparisons of WHO (2012) and DARWG radiation dose estimates indicate that the DARWG estimates are about three times the values reported in WHO (2012) based on the high-sided nature of the intake rates and dose uncertainty factors DARWG used in its estimates.

### 2.7.3. Conclusions

The discussions about monitoring of food available to DOD-affiliated individuals in Japan associated with the accident at the FDNPS support the following:

- The devastation of aquaculture and other coastal areas precluded the availability of fish from the area most heavily affected by the releases from the FDNPS for consumption by DOD-affiliated individuals.
- The U.S. DOD food procurement and distribution process protected the DOD-affiliated populations from food in transit to DOD installations.
- The implementation of FDA's Import Alert 99-33 and DOD's ALFOODACT 004-2011 barred food from affected prefectures from entering the food supply on DOD installations.
- The results of JVDC's surveys and U.S. laboratory testing for radioactivity confirmed that contaminated food did not reach DOD-affiliated individuals who purchased or consumed DOD-acquired foods. The food samples analyzed showed no detectable contamination from the FDNPS release.

- The illustrative calculations in the previous section indicate that radiation doses from food consumption, under reasonable assumptions about the potential for consuming food from the local economy in Japan are low when compared to other pathways.

The DARWG concludes that individuals in the DOD-affiliated population are very unlikely to have received radiation doses from ingesting potentially contaminated food. The DARWG recommends a case-by-case evaluation for an individual who reports having consumed food from non-DOD sources.

## 2.8 Radiological Measurements for Okinawa Prefecture and South Korea

Early in DOD response to the tsunami and FDNPS accident, USFJ recognized that radiological impact to its installations in Okinawa Prefecture and South Korea would be low. Consequently, very limited radiological sampling was conducted by the USFJ and additional response forces deployed to Japan in response to accident. Furthermore, four DARWG locations: Sasebo NB (D-14), Iwakuni MCAS (D-13), Camp Fuji (D-12), located 702, 542, and 189 miles southwest, and Misawa AB (D-1) located 228 miles north of the FDNPS had estimated whole body effective doses ranging from 0.001 to 0.009 rem (0.01 to 0.09 mSv). Among the four, the two farthest from the FDNPS had the lowest estimated effective doses of 0.001 and 0.002 rem (0.01 to 0.02 mSv), and were located west to southwest of the FDNPS where wind patterns from FDNPS are rarely favorable for airborne transport of contaminants to these locations.

Okinawa Prefecture contains hundreds of islands within the Okinawa, Miyako, and Yaeyama Island groupings as shown in Figure 19. USFJ installations are located on the largest island within the prefecture, Okinawa Island. The capital city of the prefecture is Naha, and is located in the southern portion of Okinawa Island, as shown in Figure 19. Naha is about 1,050 miles from the FDNPS; a distance 50 percent farther than that separating the FDNPS and Sasebo NB.

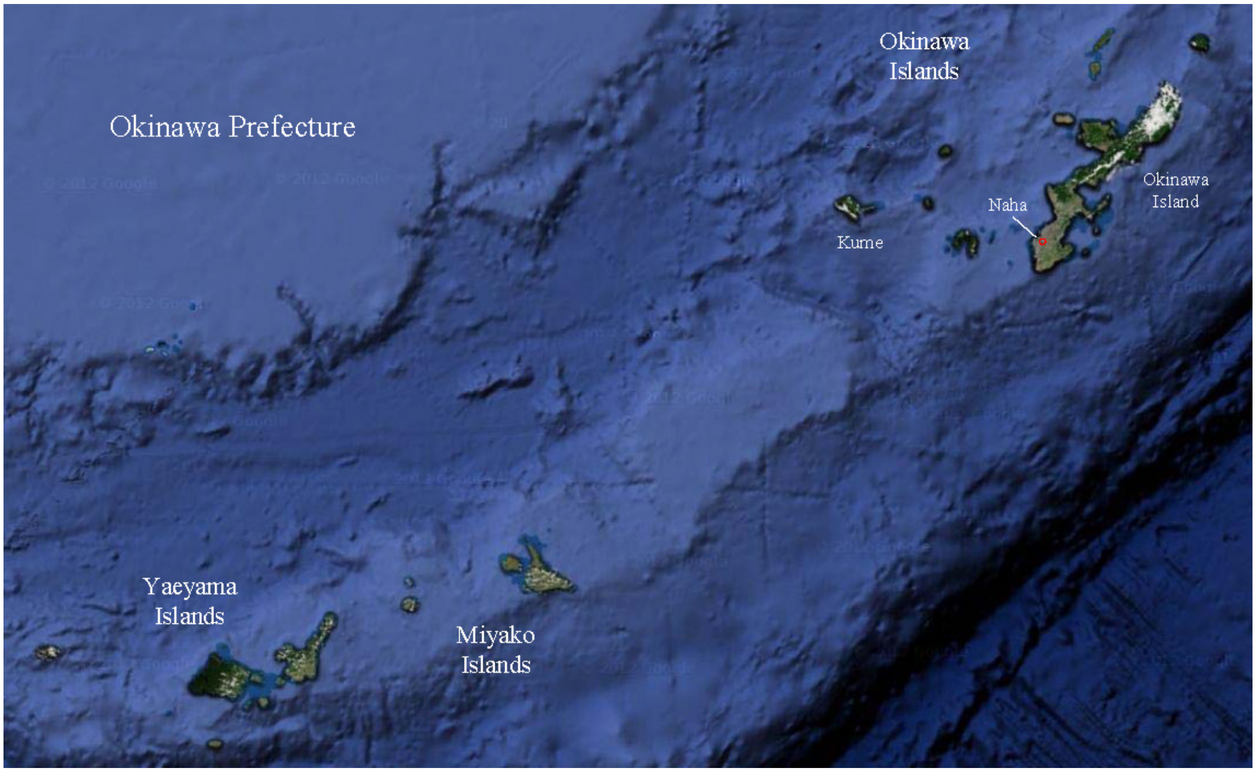


**Figure 19. Island groups in Okinawa Prefecture**

As in other Japanese prefectures, Okinawa had a MEXT external radiation monitoring station at Uruma City. Due to the negligible impacts of the atmospheric releases of radioactive materials from the FDNPS, monitoring results during the 60-day period post Tsunami were not distinguishable from the typical background measurements. This is similar to the case for the MEXT stations in Nagasaki Prefecture and Hiroshima Prefecture in which Sasebo NB and Iwakuni MCAS are located. In addition, although the DOD collected external radiation measurements at USFJ installations on Okinawa, the resulting dose rates could not be distinguished from routinely observed background rates.

Isotopic analysis of high-volume air samples was found to be a more sensitive indicator of radiological impacts than external radiation measurements for installations at large distances from the FDNPS. Table 23 lists air sampling data for selected installations. Yokota AB had recognized radiological impacts based on MEXT external radiation measurements and DOD air sampling. Iodine-131 and Cs-137 were first detected in air samples at Yokota AB on March 13, with peak concentrations measured for samples collected on March 15. Misawa AB had initial detection of I-131 on March 14, but the initial detection of Cs-137 in air samples did not occur until March 22. Activity concentrations of reactor radionuclides were substantially lower in samples collected at Misawa AB compared to Yokota AB. The maximum I-131 and Cs-137 concentrations measured at Yokota AB were 3,300 and 420-fold higher than those at Misawa AB. The primary reasons for the difference in air concentrations at the two installations is relative distance from FDNPS and favorability of weather patterns to transport radionuclides to the respective locations. Air sampling measurements were also conducted at Kadena AB on Okinawa Island. Initial detections of I-131 and Cs-137 were not made until March 25 and 27,

much later than those observed for Misawa AB and Yokota AB. The maximum concentrations for I-131 and Cs-137 in Kadena AB air samples were lower than those for Misawa AB.

**Table 23. Air sampling data for selected installations**

| Location (distance from FDNPS) | Isotope | Date of First Detect | Maximum Concentration (mBq $m^{-3}$) | Date of Maximum Concentration |
|---|---|---|---|---|
| Misawa AB (228 miles) | I-131 | March14 | $5.7 \times 10^3$ | April 14 |
| | Cs-137 | March22 | $1.5 \times 10^4$ | April 30 |
| Yokota AB (149 miles) | I-131 | March13 | $1.9 \times 10^7$ | March 15 |
| | Cs-137 | March13 | $6.3 \times 10^6$ | March 15 |
| Kadena AB (1050 miles) | I-131 | March 25 | $2.6 \times 10^3$ | April 4 |
| | Cs-137 | March 27 | $3.7 \times 10^3$ | April 4 |
| Osan AB (780 miles) | I-131 | March 15 | $2.4 \times 10^3$ | April 4 |
| | Cs-137 | March 25 | $4.2 \times 10^2$ | April 4 |

USPACOM has numerous military bases in South Korea, as shown in Figure 20. Most of the bases are located in the northwest region of the country near Seoul, the capital. Since South Korea is close to Japan, some environmental monitoring was accomplished in response to the FDNPS accident, though impacts were expected to be insignificant because weather patterns were not favorable to the transport of contaminants. Some air sampling was conducted at Osan AB, which is located south of Seoul and about 780 miles from the FDNPS. Although the first detection for I-131 occurred on March 15, Cs-137 concentrations did not reach detectable levels until March 25. The date of the maximum concentrations of I-131 and Cs-137 were on April 4, the same date as the maximum concentrations detected at Kadena AB. The maximum concentration of I-131 in air samples collected at Osan AB was similar to that for air samples collected at Kadena AB. However, the maximum Cs-137 concentration for samples collected at Osan AB was about eight times lower than for samples collected at Kadena AB.

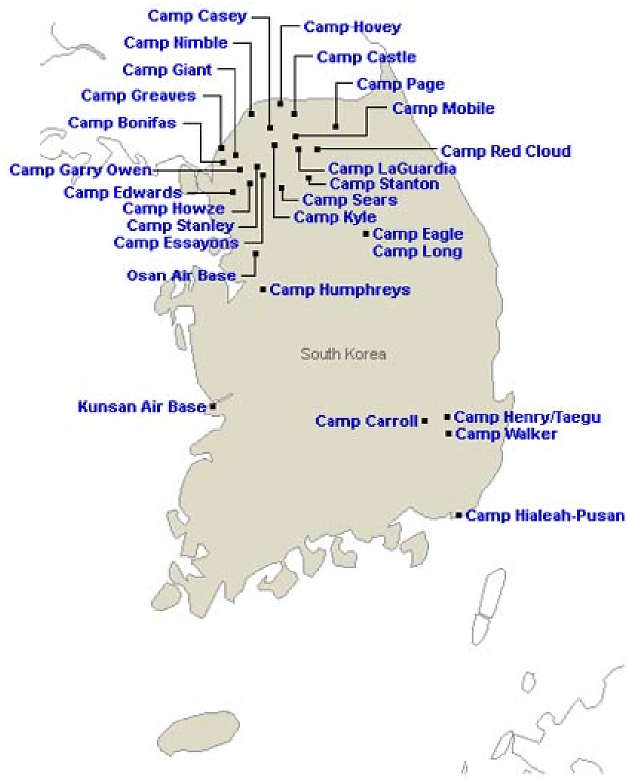


**Figure 20. USPACOM installations in South Korea**

In summary, the reactor fission products I-131 and Cs-137 were detected in environmental air samples at Kadena AB, Okinawa, and Osan AB, South Korea. The measured concentrations were similar to those detected at the installations in Japan located large distances from FDNPS, and were much less than those measured at USFJ installations in the Kanto Plain of Japan.

## 2.9 DARWG Locations

As discussed in the preceding sections, the availability and quality of environmental data for DOD shore locations are variable. The DARWG determined that the optimum method of developing doses was to consolidate the 63 locations into 14 DARWG locations, based primarily on (1) distance and direction from FDNPS, (2) availability and quality of environmental monitoring data, (3) population density of DOD-affiliated individuals, and (4) topography (coastal plain, piedmont, and mountains). The environmental data, in preferred order of use, are DOD data followed by DOE, followed by Japanese data. In most cases, the Japanese data were derived from the MEXT monitoring station closest to the DARWG location (see Table 24).

For each of the 14 DARWG location groupings, a principal site (bolded in Table 2) was chosen to identify each DARWG location and was based on DOD-affiliated population density and the location for which most of the environmental sampling was conducted.

With regard to geographical locations, most of the DARWG locations are clearly differentiated by distance from FDNPS. For the cases where this was not clear, locations were inserted into the commercial geographical information program Google Earth 2010™ to produce images that allowed for visual determination of the locations. For example, Figure 21 displays the DOD geographical locations associated with DARWG locations D-8 to D-11. Figure 22 displays the 14 DARWG locations in relation to FDNPS.

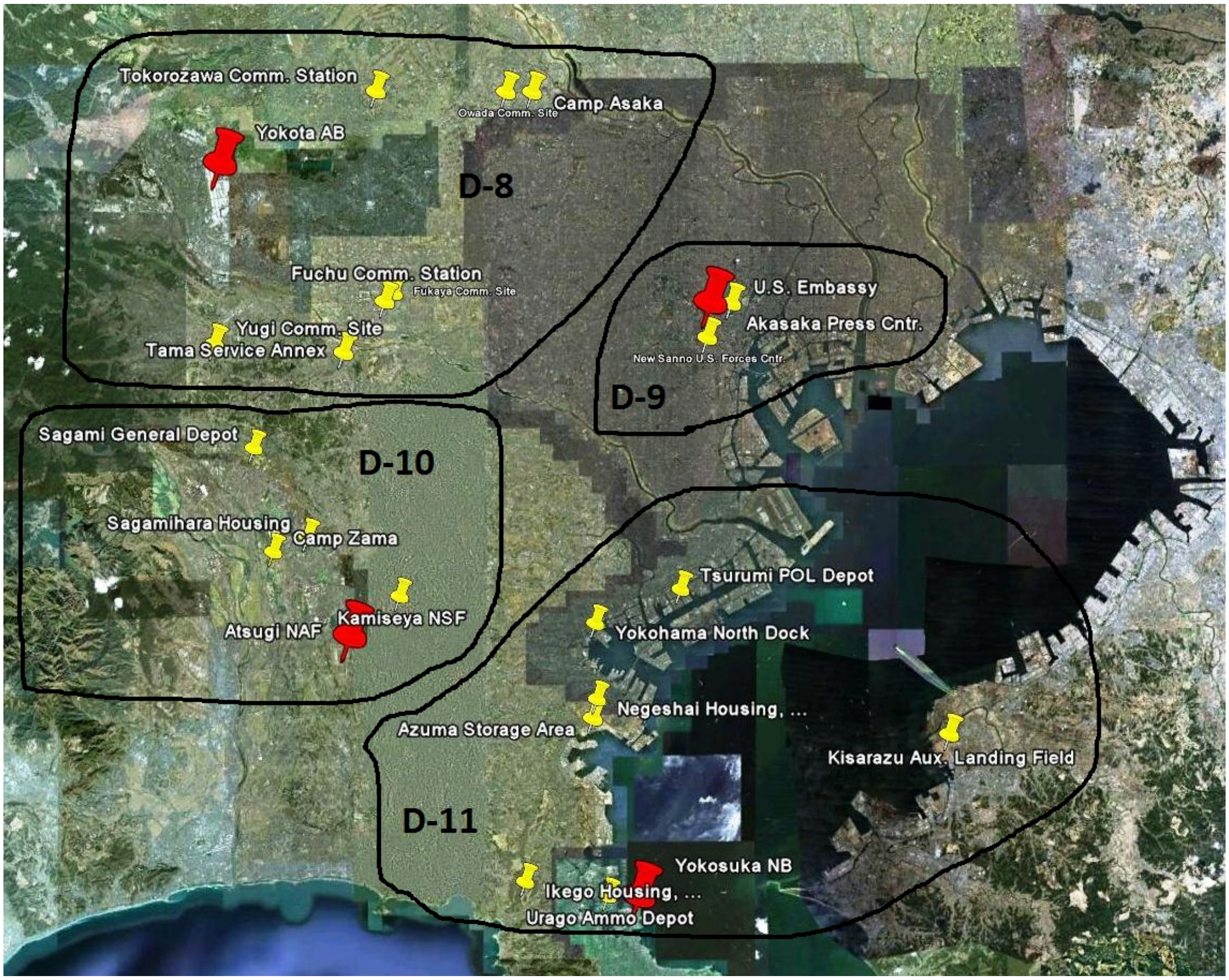


**Figure 21. DOD locations associated with DARWG locations D-8 to D-11**

J-Village (D-5) is not included in this dose assessment because there is limited environmental data available and because of its proximity to the FDNPS. Instead, personnel dosimetry data (external and internal), which are available for DOD-affiliated individuals who visited J-Village will be the primary data source for this dose assessment. Although J-Village is not included in the dose assessment for this report, it is included in the 14 DARWG locations designated in Table 24. Therefore, hereinafter the report will discuss the 13 DARWG locations for which dose calculations were performed.

**Table 24. DARWG consolidated sites and adjacent MEXT monitoring sites**

| DARWG No. | DARWG Location | Nearest MEXT/ Prefecture Number | MEXT Latitude | MEXT Longitude | Distance to MEXT (miles) |
|---|---|---|---|---|---|
| D-1 | Misawa AB | Aomori/P-2 | 40.823163 | 140.7486 | 34 |
| D-2 | Sendai Airport | Sendai/P-4 | 38.268915 | 140.86945 | 10 |
| D-3 | City of Ishinomaki | Sendai/P-4 | 38.268915 | 140.86945 | 27 |
| D-4 | City of Yamagata | Yamagata/P-6 | 38.256515 | 140.33936 | 0 |
| D-5 | J-Village | Fukushima/P-7 | 37.750358 | 140.46742 | 46 |
| D-6 | Hyakuri AB | Mito/P-8 | 36.354951 | 140.44922 | 12 |
| D-7 | City of Oyama | Utsunomiya/P-9 | 36.565806 | 139.88347 | 18 |
| D-8 | Yokota AB | Shinyuku/P-13 | 35.689509 | 139.69172 | 20 |
| D-9 | Akasaka Press Center | Shinyuku/P-13 | 35.689509 | 139.69172 | 3 |
| D-10 | Atsugi NAF | Chigasaki/P-14 | 35.333879 | 139.40470 | 8 |
| D-11 | Yokosuka NB | Chigasaki/P-14 | 35.333879 | 139.40470 | 15 |
| D-12 | Camp Fuji | Shizouka/P-22 | 34.977056 | 138.3831 | 36 |
| D-13 | Iwakuni MCAS | Yamaguchi/P-35 | 34.186068 | 131.47047 | 44 |
| D-14 | Sasebo NB | Omura/P-42 | 32.744827 | 129.87372 | 30 |
| Ref. Site | IMS | Takasaki/P-10 | 36.390749 | 139.06031 | 6 |

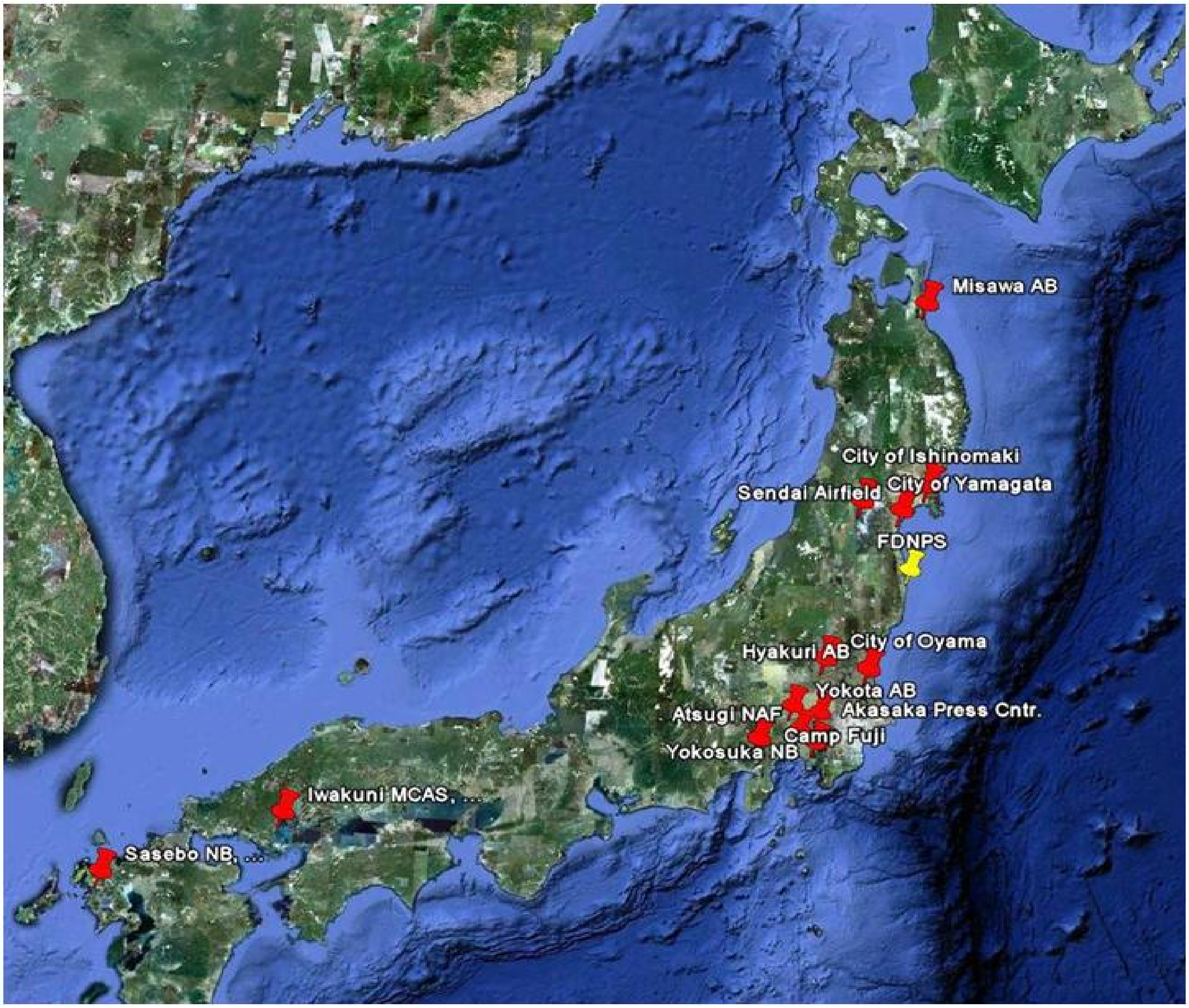


**Figure 22. Central location (red pin) of each of the 14 DARWG locations and FDNPS**

## 2.10 Summary of Environmental Data Availability

Radiological environmental data available for use in the dose calculations included external exposure data, and air, water, and soil activity concentration data. Sources of data included DOD, DOE, and GOJ. All DOD shore locations for the POI were listed in Table 2 and were consolidated into 14 DARWG locations as shown in Table 24. Environmental radiological data for all four exposure pathways were not available for every location. Table 25 lists the locations and the availability of actual measurement data. For example, external radiation exposure rate measurements were available for all locations from DOD, DOE, and GOJ MEXT sources. Table 26 shows the numbers of DOD, and DOE data values; adjusted GOJ MEXT data values were considered for the remaining points for a total of 1,440 hourly values at each location.

Environmental measurements of air, water, or soil concentrations were unavailable for some locations. As Table 25 indicates, air concentration data were available for seven of 13

locations, water concentration data were available for 11 of 13 locations, and soil concentration data were available for five of 13 locations. The available data were investigated for possible use at locations that were missing data through extrapolations based on relationships of the available data. Further details of the approaches for estimating concentrations in air, water, or soil are discussed further in Section 3.7, and in Appendix C. Limited environmental and external radiation dose data were available for J-Village. However, personal dosimeters and internal monitoring were provided for those who visited J-Village, and those results will be used in dose calculations.

**Table 25. Environmental data used for dose assessments**

| DARWG No. & | Location | External Exposure[*] | Air Concentration | Water Concentration | Soil Concentration |
|---|---|---|---|---|---|
| D-1 | Misawa AB | Yes | Yes, DOD | Yes, MEXT Aomori <MDA | No |
| D-2 | Sendai Airport | Yes | Yes, DOD | No | Yes, DOD |
| D-3 | City of Ishinomaki | Yes | Yes, DOD | No | No |
| D-4 | City of Yamagata | Yes | No | Yes, MEXT Yamagata <MDA | No |
| D-5 | J-Village | Personal Dosimeters | Internal Monitoring | N/A - No local water consumed during visit | Internal Monitoring |
| D-6 | Hyakuri AB | Yes | No | Yes, MEXT Mito | No |
| D-7 | City of Oyama | Yes | No | Yes, MEXT Utsunomiya | No |
| D-8 | Yokota AB | Yes | Yes, DOD/DOE | Yes, MEXT Shinyuku | Yes, DOD |
| D-9 | Akasaka Press Center | Yes | Yes, DOD/DOE | Yes, MEXT Shinyuku | Yes, DOD |
| D-10 | Atsugi NAF | Yes | Yes, DOD | Yes, MEXT Chigasaki | Yes, DOD |
| D-11 | Yokosuka NB | Yes | Yes, DOD | Yes - MEXT Chigasaki | Yes, DOD |
| D-12 | Camp Fuji | Yes | No | Yes, MEXT Shizouka <MDA | No |
| D-13 | Iwakuni MCAS | Yes | No | Yes, MEXT Yamaguchi <MDA | No |
| D-14 | Sasebo NB | Yes | No | Yes, MEXT Omura <MDA | No |
| Ref Site | IMS Takasaki[†] | Yes | Yes, GOJ | Yes, IMS | No |

[*]DOD, DOE, and adjusted MEXT data.
[†]CTBTO, 2011

Table 26. Numbers of measured values used in radiation dose calculations

| DARWG No. & Location | | External Dose Rate (hourly values) | | | Air DOD* | Water MEXT* | Soil DOD* |
|---|---|---|---|---|---|---|---|
| | | DOD | DOE | Adjusted MEXT | | | |
| D-1 | Misawa AB | 107 | 0 | 1333 | 52 | 60 | 0 |
| D-2 | Sendai Airport | 269 | 219 | 612 | 16 | 0 | 7 |
| D-3 | City of Ishinomaki | 66 | 84 | 950 | 19 | 0 | 0 |
| D-4 | City of Yamagata | 2 | 489 | 949 | 0 | 60 | 0 |
| D-5 | J-Village | NA | | | 0 | 0 | 0 |
| D-6 | Hyakuri AB | 0 | 3 | 1437 | 0 | 60 | 0 |
| D-7 | City of Oyama | 0 | 4 | 1436 | 0 | 60 | 0 |
| D-8 | Yokota AB | 225 | 4 | 1211 | 60 | 60 | 4 |
| D-9 | Akasaka Press Center | 89 | 225 | 1126 | 45 | 60 | 2 |
| D-10 | Atsugi NAF | 486 | 5 | 949 | 45 | 60 | 4 |
| D-11 | Yokosuka NB | 0 | 15 | 1425 | 17 | 60 | 6 |
| D-12 | Camp Fuji | 0 | 20 | 1420 | 0 | 60 | 0 |
| D-13 | Iwakuni MCAS | 0 | 398 | 1042 | 0 | 60 | 0 |
| D-14 | Sasebo NB | 0 | 0 | 1440 | 0 | 60 | 0 |

*The entries in these columns are the number of daily composite values.

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# Section 3.

# Dose Calculation Methodology

## 3.1 Overview of the Approach to the Dose Assessment

The following items list the steps involved in performing the assessment of doses for the OTR POI. Each topic is discussed in further detail in the subsequent sections.

- Describe the basic exposure model
- Describe factors affecting the dose to organs and tissues
- Identify and characterize the exposed populations
- Determine the duration of exposure
- Select dose coefficients (DC)
- Calculate the estimated doses

## 3.2 Basic Exposure Model

The basic exposure model uses a hypothetical person representative of a much larger population who:

- Is exposed to photons from a passing plume and external deposits of radioactive material;
- Breathes contaminated air from the passing plume(s) and resuspended material; and,
- Ingests radioactive material in water and soil/dust each day; and
- Ingests negligible amounts of radioactive material from food.

The total radiation dose received by any individual (or organ or tissue) is the sum of the external radiation dose and the radiation dose from radioactive material taken into the body. The total effective dose, *TED*, and thyroid dose, $H_{Thy,}$ are modeled as:

$$TED \quad = \quad 100 \times \sum_{i,j} \left\{ \left[ \left(\dot{E}_{\gamma}\right)_{j} + \left(E\dot{(\tau)}_{Inh}\right)_{i,j} + \left(E\dot{(\tau)}_{W}\right)_{i,j} + \left(E\dot{(\tau)}_{S}\right)_{i,j} \right] \times \Delta t_{j} \right\} \qquad (1)$$

$$H_{Thy} \quad = \quad 100 \times \sum_{i,j} \left\{ \left[ \left(\dot{X}_{\gamma}\right)_{j} + \left(H\dot{(\tau)}_{Thy,Inh}\right)_{i,j} + \left(H\dot{(\tau)}_{Thy,W}\right)_{i,j} + \left(H\dot{(\tau)}_{Thy,S}\right)_{i,j} \right] \times \Delta t_{j} \right\} \qquad (2)$$

where:

| | | |
|---|---|---|
| $TED$ | = | total whole body effective dose (rem) |
| $100$ | = | units conversion (rem $Sv^{-1}$) |
| $\left(\dot{E_\gamma}\right)_j$ | = | effective dose rate from external radiation for time duration $j$ (Sv $h^{-1}$) |
| $\left(E\dot{(\tau)}_{Inh}\right)_{i,j}$ | = | committed effective dose rate from inhalation for radionuclide $i$ and time duration $j$ (Sv $h^{-1}$) |
| $\left(E\dot{(\tau)}_{W}\right)_{i,j}$ | = | committed effective dose rate from water ingestion for radionuclide $i$ and time duration $j$ (Sv $h^{-1}$) |
| $\left(E\dot{(\tau)}_{S}\right)_{i,j}$ | = | committed effective dose rate from soil ingestion for radionuclide $i$ and time duration $j$ (Sv $h^{-1}$) |
| $\Delta t_j$ | = | increment of duration over which a radiation dose is estimated, and $j$ represents the $j^{th}$ interval (h) |
| $H_{Thy}$ | = | total thyroid dose (rem) |
| $\left(\dot{X_\gamma}\right)_j$ | = | external dose rate from external radiation for time duration $j$ (Sv $h^{-1}$) |
| $\left(H\dot{(\tau)}_{Thy,Inh}\right)_{i,j}$ | = | thyroid committed equivalent dose rate from inhalation for radionuclide $i$ and time duration $j$ (Sv $h^{-1}$) |
| $\left(H\dot{(\tau)}_{Thy,W}\right)_{i,j}$ | = | thyroid committed equivalent dose rate from water ingestion for radionuclide $i$ and time duration $j$ (Sv $h^{-1}$) |
| $\left(H\dot{(\tau)}_{Thy,S}\right)_{i,j}$ | = | thyroid committed equivalent dose rate from soil ingestion for radionuclide $i$ and time duration $j$ (Sv $h^{-1}$) |

As shown in Appendix C, a value was computed for each hour for each of the components above and summed over a 60-day period from March 12 through May 11, 2011. The 60-day period ending May 11, 2011 was determined in an assessment prepared by DARWG. Details are discussed further in Section 3.5. It is this summed radiation dose that is reported in this assessment. It is expected that the parameter values used in this assessment are reasonably conservative and any actual dose will be much smaller than estimated here. The parameter values used in this exposure model are presented in Table 30, and the details supporting their selection are discussed in Appendix B.

Internal radiation doses in this report are based on inhalation and ingestion rates greater than those normally used for radiation protection purposes. These increased inhalation and ingestion rates are used to estimate intakes, but the effect of intake rate on DCs is not considered. The effect of increased water consumption is expected to decrease the actual radiation doses because of the increased clearance of radionuclides from the body through urinary excretion. The effect of increased breathing rates on deposition patterns in the lung and subsequent radiation doses are not expected to differ significantly from the default values considered by the ICRP for workers and members of the public.

Doses from external gamma ray sources are based on measurements by DOD survey team personnel, measurement results obtained from the GOJ, e.g., MEXT, Nuclear and Industrial Safety Agency (NISA), etc., Japan's nuclear utilities and industry groups (i.e. TEPCO, and others), as well as U.S. agencies especially DOD and DOE. Calculations of the doses to PEPs that are presumed to have received the highest doses assume that people are exposed to the measured values for the entire duration of the assessment; no accounting is made for the shielding provided by structures and vehicles. For other PEPs, adjustments to several factors such as physical activity levels, and time spent indoors were applied. More details on how doses were calculated and a discussion of the assumptions made can be found in Appendix C.

### 3.3 Factors Affecting the Dose to Organs and Tissues

As discussed previously, radioactive materials released from the reactor core into the environment can expose people to radiation either as external sources within the passing plume or after being deposited on the ground or as internal sources when taken into the body through inhalation or ingestion of various media that have become contaminated (e.g., the air they breathe or the water or dirt they ingest).

The radiation doses received by an individual from those sources are generally characterized either in terms of effect on the entire body or effect on individual bodily organs or tissues. The dose from external sources is generally characterized as the dose to the whole body and is expressed as effective dose. Doses from internal sources are characterized by the dose to individual organs or tissues, and depend on the amount of material taken into the body and on the distribution throughout the body to various organs and tissues. These internal doses are generally characterized either as "committed effective doses" to represent the contribution to overall effect on the body as a whole, or as "equivalent doses" to the individual organ or tissue.

The radioactive materials released during a nuclear reactor accident vary across a full spectrum of elements and their compounds, as well as in the variety of radionuclides with their respective radioactive decay half-lives, and physical properties. In order to deliver a dose to an organ or tissue, radioactive materials inside the body must reach the organ or tissue so that the organ or tissue will receive its dose. Some radioactive materials distribute almost uniformly throughout the body while others tend to concentrate and accumulate in specific organs. Those that distribute uniformly include radionuclides of cesium (e.g. Cs-134 and Cs-137). Those that tend to accumulate in specific organs include those from iodine (I-131, I-132, etc.) that accumulate in the thyroid gland, strontium (e.g., Sr-89 and Sr-90) that accumulate in the bones, and others.

Table 27 lists the relative contributions of selected radionuclide groups to the concentrations of radioactive materials in the air, water, and soil at Yokota AB (D-8). The tables also list the relative contributions of these radionuclide groups to the committed effective dose and committed equivalent dose to the thyroid from inhalation of air and ingestion of water and soil. These tables illustrate the significance of the relative contributions of the radioisotopes of iodine to concentrations in air (65.7 percent), water (86.3 percent) and soil (50.6 percent). Iodine's relative contributions to the total activity concentrations in the three media indicate the importance of iodine to evaluating the doses from the FDNPS accident.

Even more dramatic are iodine's relative contributions to the committed equivalent dose to the thyroid from inhalation of air (92.7 percent), ingestion of water (99.4 percent), and ingestion of soil (95.0 percent). Not only are these relative contributions significant, but the total committed equivalent doses at each location are substantially greater than their corresponding total committed effective doses (approximately 20 times in all cases). Furthermore, since iodine accumulates in the thyroid gland, its dose is the one of most concern for potential health effects; namely thyroid cancer. Therefore, it is very important that the doses to the thyroid gland are expressed properly. Table 28 lists the contributions to dose and the percent contribution from exposure to external sources and to internal sources of radiation (inhalation of air, and ingestion of water and soil). Figure 23 illustrates the contributions to whole body effective dose from all sources, and Figure 24 provides similar information for thyroid dose.

**Table 27. Relative contributions of radionuclide groups to concentration, committed effective dose and committed equivalent dose to the thyroid at Yokota AB (D-8)**

| | Air Inhalation | | | Water Ingestion | | | Soil Ingestion | | |
|---|---|---|---|---|---|---|---|---|---|
| **Radionuclide** | **[A]*** | **$E(\tau)$†** | **$H_{T,\tau}$‡** | **[A]*** | **$E(\tau)$†** | **$H_{T,\tau}$‡** | **[A]*** | **$E(\tau)$†** | **$H_{T,\tau}$‡** |
| All Iodine | 65.7% | 84.7% | 92.7% | 86.3% | 89.7% | 99.4% | 50.6% | 70.1% | 95.0% |
| All Tellurium | 29.1% | 9.5% | 7.0% | - | - | - | 24.6% | 5.9% | 3.3% |
| All Cesium | 4.3% | 5.8% | 0.3% | 13.7% | 10.3% | 0.6% | 24.8% | 24.0% | 1.6% |
| All Others | 0.9% | 0.1% | 0.0% | - | - | - | - | - | - |
| Total | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% | 100% |
| Dose (rem) | N/A | 0.018 | 0.33 | N/A | 0.010 | 0.172 | N/A | <0.001 | 0.0015 |

*[A] percent of total activity concentration in the stated medium for this radionuclide group
†$E(\tau)$ percent of total committed effective dose from the route of entry for this radionuclide group
‡$H_{T,\tau}$ percent of total committed equivalent dose to thyroid from the route of entry for this radionuclide group

**Table 28. Contributions to doses from external and internal radiation at Yokota AB (D-8)**

| **Source** | **Dose (rem)** | | **Percent Contribution** | |
|---|---|---|---|---|
| | **$E(\tau)$*** | **$H_{T,\tau}$†** | **$E(\tau)$*** | **$H_{T,\tau}$†** |
| External Radiation | 0.027 | 0.027 | 49.7 | 5.2 |
| Internal Radiation | | | | |
| Inhalation | 0.018 | 0.328 | 32.4 | 62.0 |
| Water Ingestion | 0.010 | 0.172 | 17.7 | 32.5 |
| Soil Ingestion | <0.001 | <0.001 | 0.2 | 0.3 |
| Total Internal | 0.028 | 0.502 | 50.3 | 94.8 |
| Total | 0.055 | 0.530 | 100 | 100 |

*$E(\tau)$ effective dose from external radiation or committed effective dose from internal exposure
†$H_{T,\tau}$ equivalent dose from external radiation or committed equivalent dose from internal exposure to the thyroid

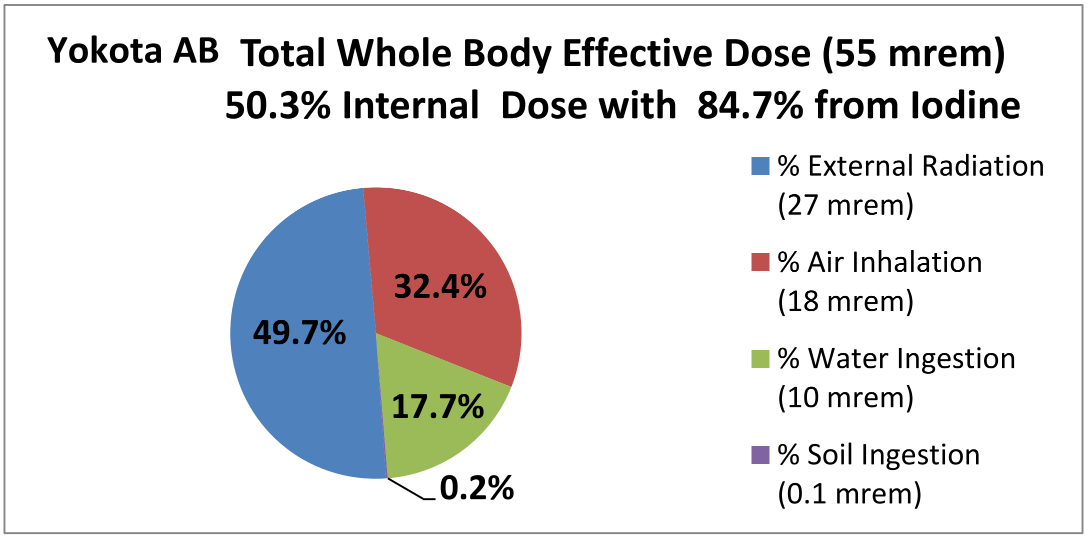


**Figure 23. Percent contributions from external, air, water, and soil pathways to whole body effective dose**

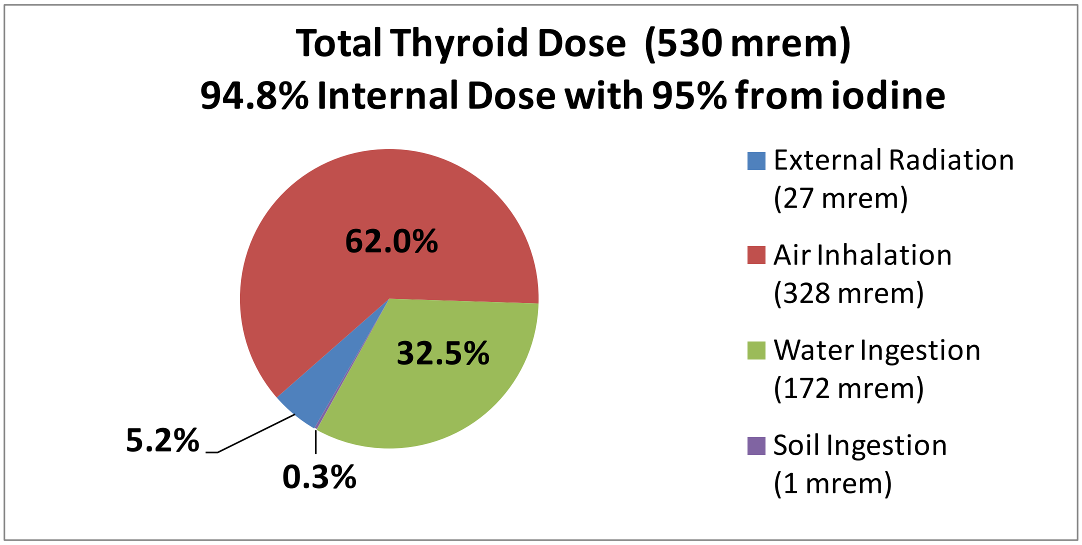


**Figure 24. Percent contributions from external, air, water, and soil pathways to thyroid dose**

Table 29 lists the committed equivalent dose to organs and the committed effective dose for individuals performing PEP Category 2, adult, humanitarian relief work at Yokota AB (D-8), which is located in the Kanto Plain. It is clear from this table, that the thyroid dose is about 40 times larger than the dose to any other organ, and is the most appropriate dose for assessing potential health effects.

**Table 29. Committed equivalent dose to organs for adults humanitarian relief work at Yokota AB (D-8)**

| Organ | Dose (rem)[mSv] | Organ | Dose (rem) [mSv] |
|---|---|---|---|
| Adrenals | 0.007 [0.07] | Ovaries | 0.008 [0.08] |
| Bladder Wall | 0.016 [0.16] | Pancreas | 0.008 [0.08] |
| Bone Surface | 0.013 [0.13] | Red Marrow | 0.009 [0.09] |
| Brain | 0.006 [0.06] | ET Airways | 0.038 [0.38] |
| Breast | 0.005 [0.05] | Lungs | 0.008 [0.08] |
| Esophagus | 0.007 [0.07] | Skin | 0.005 [0.05] |
| St Wall | 0.008 [0.08] | Spleen | 0.007 [0.07] |
| SI Wall | 0.008 [0.08] | Testes | 0.006 [0.06] |
| ULI Wall | 0.01 [0.1] | Thymus | 0.007 [0.07] |
| LLI Wall | 0.016 [0.16] | Thyroid | 1.51 [15.1] |
| Colon | 0.012 [0.12] | Uterus | 0.008 [0.08] |
| Kidneys | 0.008 [0.08] | Remainder | 0.009 [0.09] |
| Liver | 0.007 [0.07] | Effective dose* | 0.083 [0.83] |
| Muscle | 0.007 [0.07] | | |

*Effective dose from internal radionuclides (Does not include the contribution to effective dose from external radiation).

## 3.4 Exposed Populations

### 3.4.1. Population of Interest

The POI is the entire population of DOD-affiliated individuals (Service members, civilian employees, families of Service members and civilian employees, and contractor employees) on the four main islands of Japan (Hokkaido, Honshu, Shikoku, and Kyushu), in aircraft entering the warm or hot zones, and on USN vessels in the area during the incident. For this report, only the shore-based individuals are considered because data for shipboard and air flight individuals were not available or evaluated at the time of preparing this report. Location and duty information pertaining to actual individuals (shore-based) is not needed to calculate radiation doses at this time because radiation doses estimated in this study are representative of radiation doses potentially received by a “person of reasonably high-end behavior.” (EPA, 2011) The dose estimates presented here are based on the environmental radiation conditions measured between March 12, 2011 and May 11, 2011.

3.4.2. Potentially Exposed Populations

A PEP is a subpopulation of the POI that is defined by a particular set of characteristics, common locations, exposure scenarios, and habit data[12] within the larger POI for OT. Members of a PEP are likely to be exposed to the same radiation sources; however, the environmental radiation data are not part of the definition of a PEP. It is acknowledged that within a PEP actual radiation doses to real individuals will vary widely; however, the dose assessment process is intended to produce a credible (NCRP, 2009a) radiation dose for a PEP. The relationship between the PEPs and the POI is shown in Figure 25.

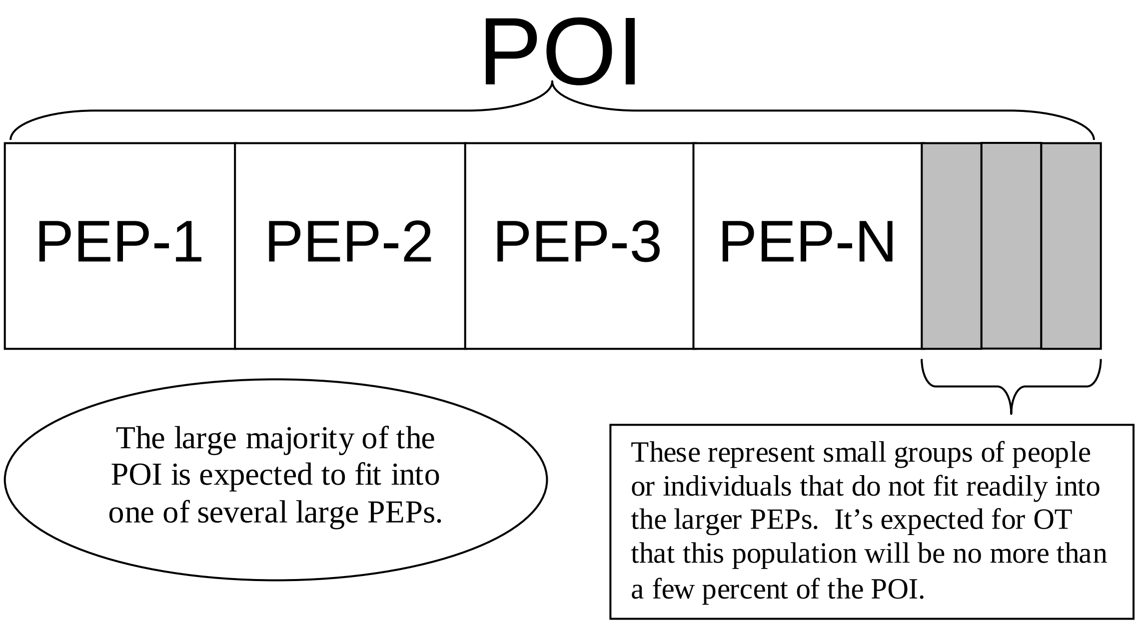


**Figure 25. Relationship of the POI and related PEPs**

The preparation of estimated doses for the location-specific PEPs involves assumptions about the values for the numerous parameters required for calculations. In this report, estimates of doses involve the selection of parameter values that are reasonable overestimates of the actual values or ranges of values. The details of the parameter value selection for the PEPs are discussed in Appendix B.

Because the parameters (inhalation, water consumption, and soil ingestion rates) that describe general habit data are independent of location the PEPs were grouped into broad population-based categories. Recall, that, as discussed in Section 2.7, food intake is not considered. These PEP categories were a convenience for grouping PEPs into broad categories

[12] "Habit data" is a broad term used to describe those conditions that bring members of the public in contact with radiation or radioactive material. Commonly used habit data are ingestion and inhalation rates, time spent indoors and time spent outdoors. See, for example, *Radiological Conditions in Areas of Kuwait with Residues of Depleted Uranium* (IAEA, 2003) and *Generalised Habit Data for Radiological Assessments* (Smith, 2003).

during the initial PEP creation stage of the dose assessment. Once individual PEPs are created and the registry populated the need for the PEP categories ends. An example of the relationship between the PEP categories and PEPs is shown in Figure 26.

A PEP is defined as a PEP category and a DARWG location; for example, PEP Category 1 individuals at DARWG Location D-8, called Yokota AB and which includes locations L-16 through L-23 form the PEP with the following characteristics:

- Military members (adults greater than seventeen years old) living and working on or near Yokota AB with duties limited to their routine military duties;
- Non-military adults, adults greater than 17 years old, living and working in or near a military installation; and
- Non-military adult workers involved in moderate to heavy, outdoor work activities on or near a military installation.

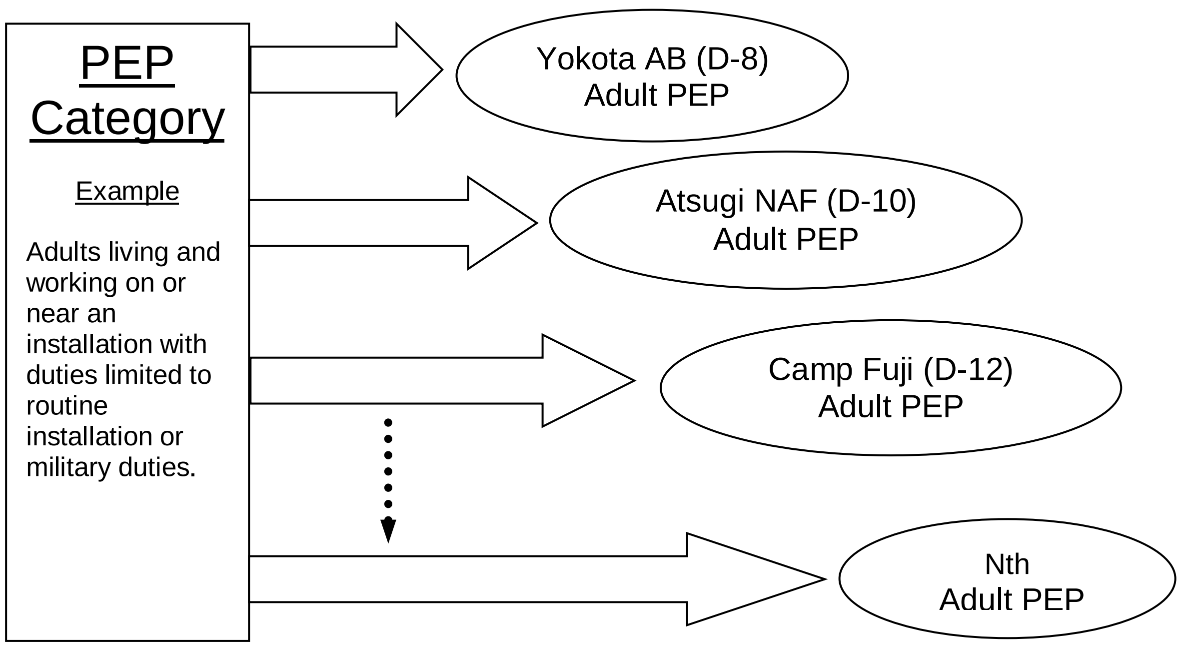


**Figure 26. Example relationship between PEP categories and PEPs**

The description of these categories and parameter values are shown in Table 30; and the details and rationales behind the selection of parameter values are discussed in Appendix B.

The time spent indoors is presented as a function of the ICRP age groups and is described as “none, lower, mean and upper” corresponding to no time spent indoors, the 5$^{th}$ percentile of the time spent sleeping/napping, the mean value, and the 95$^{th}$ percentile value reported in EPA (2011). In this report, the term “upper percentile” is taken from the 2011 edition of EPA’s Exposure Factors Handbook (EPA, 2011) and is used “to represent values in the upper tail (i.e., between the 90$^{th}$ and 99.9$^{th}$ percentile) of the distribution of values for a particular exposure

factor." The mean and 95th percentile values were taken from the table of recommended values (Table 16.1, [EPA, 2011]), and the 5th percentile values were taken from Tables 16.25 and 16.26 of EPA (2011). When a choice of values is given (e.g., when more than one EPA age group is subsumed into an ICRP age group), the minimum value was chosen because time spent indoors offers some protection against radiation exposure and the intent is to overestimate the radiation dose if there is any ambiguity. The details of these data are found in Appendix B.

**Table 30. Potentially Exposed Population (PEP) categories and parameter values considered for this report**

| Category | Description | | | | |
|---|---|---|---|---|---|
| 1 Adults, Routine Activities | Military members, adults greater than 17 years old, living and working on or near an installation with duties limited to their routine military duties. | | | | |
| | Non-military adults, adults greater than 17 years old, living and working in or near a military installation. | | | | |
| | Non-military adult workers involved in moderate to heavy, outdoor work activities on or near a military installation. | | | | |
| Parameter values for Category 1 | Inhalation Rate:<br>Drinking Water Ingestion Rate:<br>Soil Ingestion Rate: | $30\ m^3\ d^{-1}$<br>$4\ L\ d^{-1}$<br>$200\ mg\ d^{-1}$ | | | |
| 2 Adults, Humanitarian Relief Efforts | Military personnel participating in long-term humanitarian aid missions restricted to one location. This PEP is meant to capture the radiation dose at a single location. Individuals involved in humanitarian relief missions in different locations should consider their doses to be no greater than the maximum value listed in Table 35 and Table 36. | | | | |
| Parameter values for Category 2 | Inhalation Rate:<br>Drinking Water Ingestion Rate:<br>Soil Ingestion Rate: | $32\ m^3\ d^{-1}$<br>$6\ L\ d^{-1}$<br>$500\ mg\ d^{-1}$ | | | |
| 3–7 Children, Routine Activities | Children living on a military installation. This PEP is stratified into specific age ranges of 3 months, 1, 5, 10, and 15 years old to account for different lifestyle or habit data and dosimetric data. | | | | |
| Parameter values for Categories 3–7 | PEP Category | ICRP Age | Inhalation Rate ($m^3\ d^{-1}$) | Drinking Water Ingestion Rate ($L\ d^{-1}$) | Soil Ingestion Rate ($mg\ d^{-1}$) |
| | 3 | 3 mo | 9.2 | 1.2 | 1000 |
| | 4 | 1 y | 12.8 | 0.89 | |
| | 5 | 5 y | 13.8 | 1.0 | |
| | 6 | 10 y | 16.6 | 1.4 | |
| | 7 | 15 y | 21.9 | 2.8 | |

- The parameter values and rationales for all these categories are shown in Appendix B.
- The PEP category for individuals on naval vessels at sea, and in flight crews are not considered here as discussed in Section 3.4.1.
- A PEP for doses to the fetus and infants from the ingestion of mother's milk will be considered in a future report.

Figure 27 and Figure 28 illustrate the schematic relationships among the DARWG locations, the population age groups, physical activity levels, and time spent indoors.

**Table 31. Physical activity level definitions**

| Physical Activity Level | Definition |
|---|---|
| Inactive | 25$^{th}$ percentile values for breathing rates, drinking water ingestion rates, and soil ingestion rates. See Appendix B for details. |
| Low activity | 50$^{th}$ percentile or central tendency for values breathing rates, drinking water ingestion rates, and soil ingestion rates. See Appendix B for details. |
| Medium activity | 75$^{th}$ percentile or high end behavior values for breathing rates, drinking water ingestion rates, and soil ingestion rates. See Appendix B for details. |
| High activity | 95$^{th}$ or “upper” percentile values for breathing rates, drinking water ingestion rates, and soil ingestion rates. See Table 30 and Appendix B for details. |
| Extreme activity | Humanitarian relief values for breathing rates, drinking water ingestion rates, and soil ingestion rates. See Table 30 and Appendix B for details. |

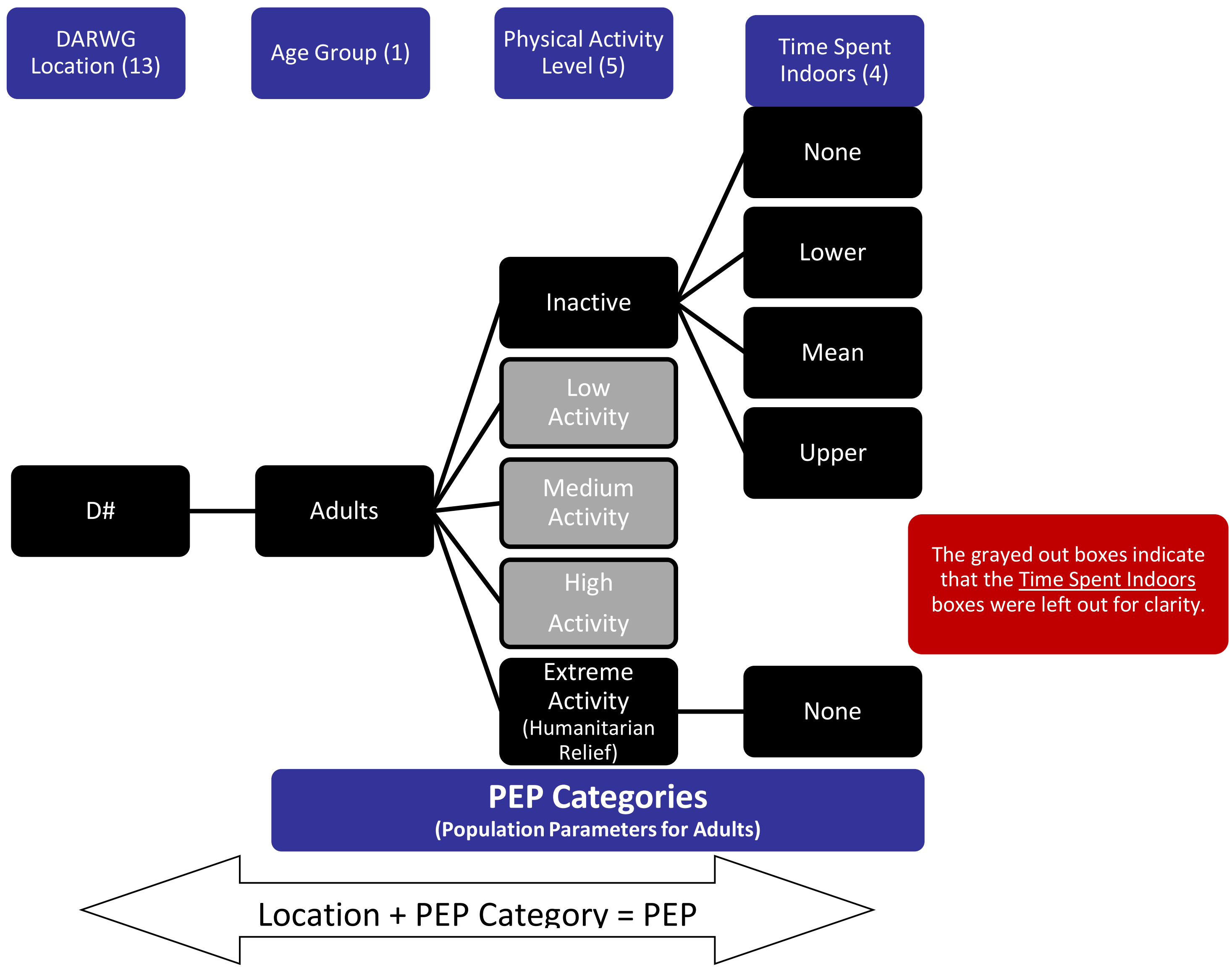


**Figure 27. PEP schematic for adults**

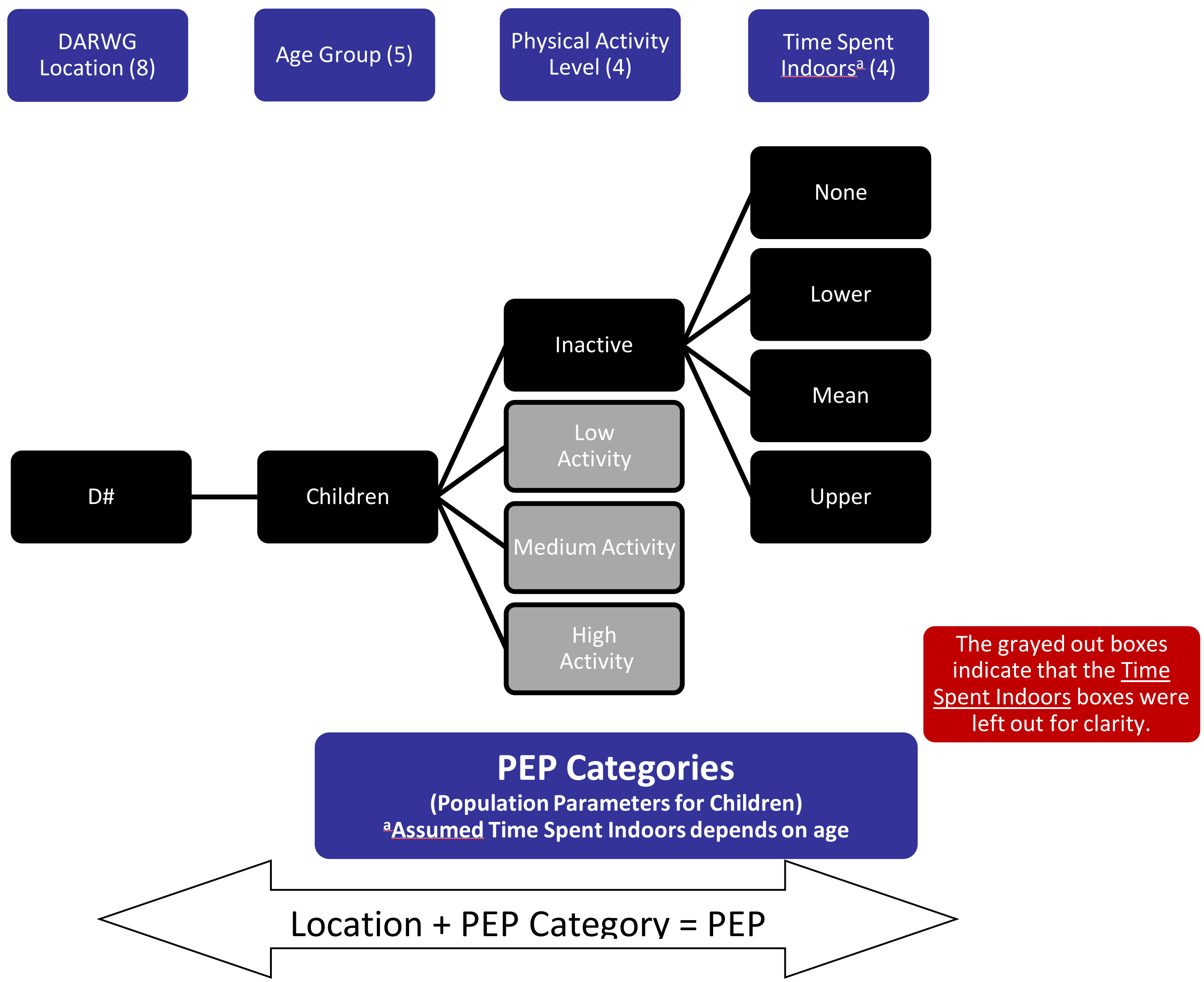


**Figure 28. PEP schematic for children**

For adults at each of the 13 DARWG locations, there are the following groups.

1. A group with four levels of physical activity subdivided into four discrete “time spent indoors” blocks. This yields (13 locations) × (1 age group) × (4 levels of physical activity) × (4 “times spent indoors”) for a total of 208 PEPs.
2. A group with 13 locations, 1 age group, 1 level of physical activity, and 1 “time spent indoors” for a total of 13 more PEPs (13 × 1 × 1 × 1).

The total number of PEPs for adults is therefore 221.

For children at each of the eight DARWG locations where children were expected, there are eight DARWG locations, five age groups, three levels of physical activity, and four discrete “time spent indoors” blocks. This yields (8 locations) × (5 age groups) × (4 levels of physical activity) × (4 “times spent indoors”) for a total of 640 PEPs for children.

Adding the total PEPs for adults and children results in a grand total of 861 PEPs.

## 3.5 Duration of Exposure

The sequence of radioactive material releases associated with the accident at FDNPS involved a series of episodic events resulting in airborne concentrations of radioactive materials that were dispersed by weather patterns over significant portions of the four main islands of Japan and the neighboring seas. Extensive monitoring of radiation exposure rates and airborne concentrations of radioactive material was conducted by GOJ agencies (e.g. MEXT, NISA, etc.), Japan’s nuclear utilities and industry groups (e.g., TEPCO and others), as well as U.S. agencies especially DOD and DOE. Review of the monitoring results at the locations of substantial populations of U.S. citizens and U.S. facilities in the areas surrounding Tokyo, such as Yokota AB and Yokosuka NB, showed that exposure rates appeared to decrease at a relatively stable rate starting in late March 2011, as illustrated in Figure 29.

Recognizing that these stabilizing exposure-rate patterns may have represented the initial stages of elevated normal exposure rate, the OTR Steering Group overseeing the development of the OTR tasked DARWG to prepare a recommendation for the possible end date for consideration of exposed individuals in the OTR.

DARWG reviewed and used available environmental radiation data (concentrations in air, water, and soil; exposure rate) to develop a recommendation that the period of consideration for inclusion of both radiation monitoring data and individuals who were on or near the four main islands of Japan in the OTR should be from March 12, 2011 to May 11, 2011 (60 days). This recommendation was then accepted by the OTR Steering Group.

The recommendation to begin the period on March 12 recognizes the results of available external radiation exposure rate measurements, which exhibit reasonably consistent, low-levels before about March 15. These observations, as illustrated the plots in Appendix F, provide convincing evidence that the exposures of concern were not present before March 15 and made selection of the start date of March 12 a conservative assumption about the start of potentially significant doses.

The recommendation to end the OTR period on May 11 was based on the observation that the total effective dose calculated for the 365 days following each day at Yokota AB and Yokosuka AB did not change by more than 0.001 rem (0.01 mSv) after May 11, 2011, as illustrated in Figure 30.

The calculation methods used were fundamentally the same as the ones used in this report for calculating doses. They differ in that they were not quite as refined and did not take into account some of the more detailed aspects of the calculations, such as, for example, adjusting for gaseous fractions of iodine. However, the dose values were not critically important for determining the OTR period because refinements in the calculations would neither affect the trends observed nor invalidate the conclusions reached based on the initial calculations.

More details for the OTR period calculation can be found in DARWG (2011a).

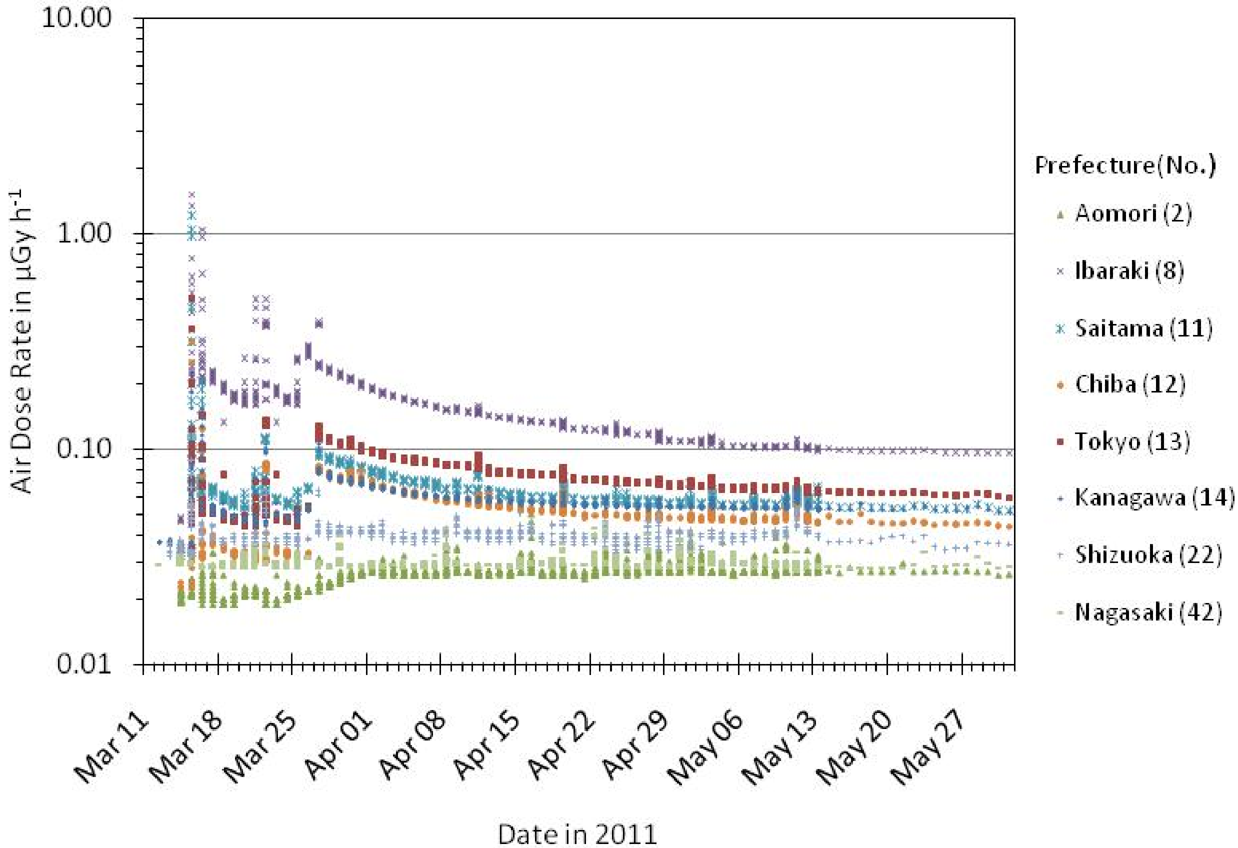


**Figure 29. External radiation dose rates from MEXT data in prefectures with DOD-affiliated individuals**

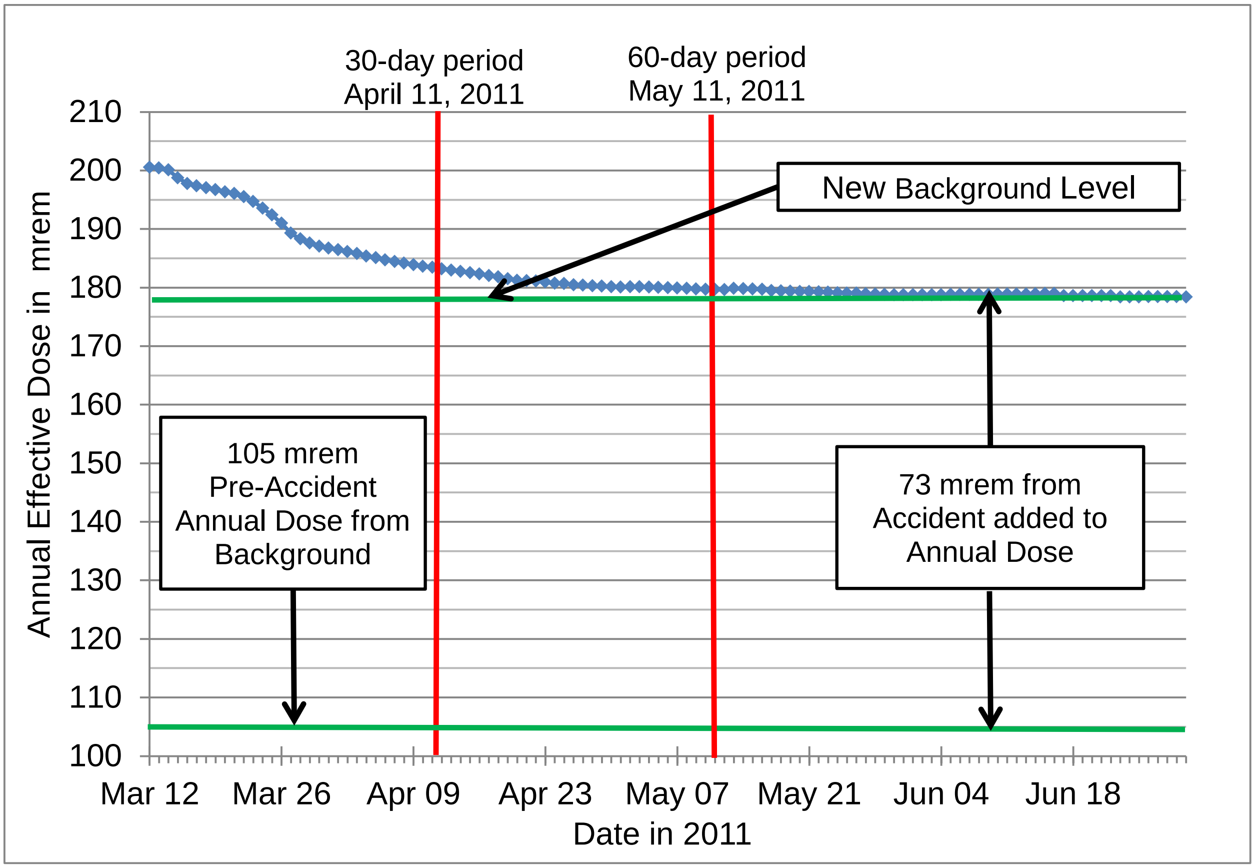


**Figure 30. Estimated total effective dose for the 365-day period beginning each day after March 11 at Yokota AB**

### 3.6 Dose Coefficients

The dose coefficients (DC) used in calculations of committed effective dose and committed equivalent dose were taken from the following ICRP databases of DCs:

- CD-ROM 1: workers and members of the public; the "Results are essentially the same as the latest ICRP advice given in Publications 68 (workers) and 72 (members of the public). The database extends the results given in these Publications [sic] to include DCs for ten aerosol sizes and for ten times after intake." (ICRP, 2001) The DCs provided in this database are provide for the following ages: 3 mo (birth to 1 y), 1 y (>1 y to 2 y), 5 y (>2 y to 7 y), 10 y (>7 y to 12 y), 15 y (>12 y to 17 y), and adults.
- CD-ROM 2: embryo and fetus; "contains committed equivalent doses per unit intake (DCs) to various tissues and committed effective doses per unit intake (DCs). Results are given for both workers and members of the public. [This distinction accounts for different patterns of aerosol deposition in the lungs.] Results are consistent with the latest ICRP advice given in Publication 88. The database extends the results given in the Publication to include DCs for ten aerosol sizes and for five post natal times after intake." (ICRP, 2003)

- CD-ROM 3: infants from radionuclides in mother's milk; "contains committed equivalent doses per unit intake (DCs) to various tissues and committed effective doses per unit intake (DCs). In this database, the intake is received by the mother, while the dose is calculated to the infant. Results are given for both workers and members of the public. Results are consistent with the latest ICRP advice given in Publication 95. The database extends the results given in the Publication to include DCs for ten aerosol sizes and for five integration periods after intake." (ICRP, 2007b).

## 3.7 Dose Calculations

To calculate the whole body effective and thyroid doses, the basic exposure model presented in Section 3.2 was automated by the use of macro-assisted spreadsheets that explicitly calculate external radiation doses and internal radiation doses from inhalation, ingestion of water, and ingestion of soil and dust, and include adjustments for time spent indoors. See Appendix C for the details.

# Section 4.

## Quality Assurance

Quality assurance occurred early in the operation. Local reviews occurred before the environmental monitoring data were released to USFJ for consolidation on a daily basis. USFJ performed daily reviews, verification, and consolidation of the environmental radiation data. These data were eventually received by the DARWG for verification, validation and potential use. Similar reviews of external and internal personnel monitoring data also occurred, although at different times and frequencies.

During Operation Tomodachi there were many DOD elements involved in environmental and personnel monitoring. The DARWG identified differences among the services' operating procedures, equipment, and personnel qualifications, and DARWG developed a quality assurance plan for the review and analysis of data from environmental radiation monitoring, external and internal personnel radiation monitoring, and personnel tracking (DARWG, 2011b). This plan was developed to ensure accuracy, reliability, appropriateness, and reasonableness to withstand technical peer review. Defense Manpower Data Center (DMDC) personnel location data and DOE and Japanese environmental data were also included in this process as an external check on reasonableness.

Two DARWG members were assigned the responsibility for verifying and validating all data from a military service. These members were tasked to characterize the data quality. This data characterization was required to determine which data should be employed in the dose assessment process.

Two DARWG members also visited each service's centralized external dosimetry processing and environmental laboratories to review standard operating procedures, accreditation, chain of custody, and treatment of samples. The DARWG also visited the Naval Dosimetry Center to review internal monitoring data validation procedures.

DARWG dose calculations were performed by two independent teams, using different commercial software tools: Microsoft Excel and PTC Mathcad. These independent calculations were then compared as part of the dose validation process. Excel worksheets supported the deterministic dose results reported in this technical report. Mathcad worksheets supported the probabilistic dose results to be reported in the follow-on DARWG publication DTRA-TR-12-002, *Probabilistic Analysis of Radiation Doses for Shore-Based Individuals in Operation Tomodachi*.

During the development of this report the World Health Organization released its preliminary dose estimate. Although WHO's dose estimate was based on different periods of exposure, populations, and locations, there were enough similarities to serve as a comparative validation of the DARWG's dose effort.

Finally, two external peer-review groups reviewed this effort. A preliminary review was provided the Veterans' Advisory Board on Dose Reconstruction, Subcommittee No. 1 (VBDR, 2012), followed by a more extensive review by NCRP Scientific Committee No. 6-8 (NCRP, 2012).

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# Section 5.

## Data Analysis

### 5.1 Introduction

Environmental radiological data used in the dose calculations included the results of external radiation exposure rate, and air, water, and soil activity concentration measurements. Sources of data included DOD, DOE, and GOJ teams. All DOD shore locations for the POI listed in Table 2 were consolidated into 14 DARWG locations as shown in Table 24. Figure 22 shows the FDNPS and the 14 DARWG locations on a map of Japan, and is helpful in understanding the discussions that follow.

External radiation exposure data were available at the IMS and at all DARWG sites except very limited data at J-Village (D-5). However, not all locations had the other environmental radiological data (air, water, or soil activity concentration data) available. Table 25 indicates the locations at which actual measurement data were available. Table 26 lists the numbers of hourly external radiation exposure values used at each location and the numbers of daily values of air, water, and soil concentration measurements used at each location. When air, water, or soil environmental measurements were not available at a particular DARWG location, dose ratios were used to determine committed effective doses (see Appendix C, Section C-7) and activity concentration weighted dose coefficients were used to calculate thyroid committed equivalent doses (see Appendix C, Section C-13) for individuals at those locations.

Very limited environmental radiation data were collected for J-Village, but were not readily available at the time dose calculations were being performed. However, all U.S. DOD-affiliated individuals entering J-Village were issued dosimeters and underwent internal monitoring. Therefore, personal dosimeter and internal monitoring results will be used to calculate doses in a report to be published by the end of calendar year 2012.

The environmental radiological measurement data were analyzed to assess their overall reliability and to evaluate whether trends in the various parameters were consistent with expected behavior of radioactive materials released into the atmosphere and dispersed over distance and time. The following sections discuss the analysis of the reliability of the environmental monitoring data and the relationship of dose, if any on the distance from the FDNPS and time following the release of material.

### 5.2 Environmental Monitoring Data Analysis

#### 5.2.1. External Radiation

External radiation exposure rates for 13 DARWG locations are shown in Appendix F. The data in those figures show that the major radioactivity releases occurred between March 12 and March 25 with notable amounts on about March 15 and 24 followed by fairly steadily decreasing rates through April and May that resemble the radioactive decay of longer lived radionuclides. The exposure rates plotted in those figures represent the results of data selection

from DOD and DOE sources and consolidation with adjusted results from the nearest MEXT monitoring station to the specified DARWG location as discussed in Section 2.3.

External exposure rates for City of Yamagata (D-4), Sendai Airport (D-2), and City of Ishinomaki (D-3), which are 69, 50, and 72 miles northwest to northeast from the FDNPS show consistent trends and magnitudes in hourly data. Corresponding data for Misawa AB (D-1), which is about 150 miles north of FDNPS, show much lower external radiation dose rates.

IMS Takasaki RN38**,** City of Oyama (D-7)**,** and Hyakuri AB (D-6) are 133, 102, and 92 miles from southwest to southeast from the FDNPS and show slightly different external radiation dose with distance.

Yokota AB (D-8), Atsugi NAF (D-10), and Akasaka Press Center (D-9) are 149, 160, and 142 miles southwest to southeast from the FDNPS, and have external dose rates that are quite similar, leading to external radiation doses of 0.027, 0.018, and 0.018 rem (0.27, 0.18 and 0.18 mSv).

Camp Fuji (D-12) at 189 miles southwest and Yokosuka NB (D-11) at 165 miles south southwest have external radiation dose rates leading to external doses of 0.006 and 0.012 rem or 0.06 and 0.12 mSv.

The DARWG locations that are the farthest from the FDNPS are Iwakuni MCAS (D-13) at 542 miles and Sasebo NB (D-14) at 702 miles southwest, show essentially no measurable increase in external radiation dose rates above the pre-incident background levels.

As shown in Table 25 and Table 26 and displayed in the figures in Appendix F, external radiation dose rate results were quite robust for all locations and supported the dose calculations. Even data for Misawa AB (D-1) and Sasebo NB (D-14) provide credible support for the almost total lack of impact from the FDNPS accident on those locations.

The collection of exposure rate measurements at the 13 DARWG locations support assumptions about the arrival times of airborne radioactive materials released from FDNPS. Overall, the variations by location showed relative consistency across regions, such as for the four DARWG locations (D-8 through D-10) in the Kanto Plain. Exposure rates at non-MEXT locations, such as at stations of the System for Predictions of Environmental Emergency Dose Information (SPEEDI) near Yokota AB (D-8) and Yokosuka NB (D-11) were compared with exposure rates obtained at the corresponding MEXT stations. External doses for the 60-day OTR period agreed within 10 percent (Chehata et al., 2012) DARWG considers this observation as sufficient support for assumptions used in deriving external exposure rates, and air concentrations for times without reliable measurements using results of other, reasonably nearby locations.

### 5.2.2. Air

Air concentrations were available from monitoring by DOD, DOE, and other organizations for seven DARWG locations and for the IMS Takasaki RN38 station as listed in Table 25. Those data were characterized by:

- Objectives that ranged from quick assessments to support decision making to sophisticated techniques intended to support scientific evaluations of dose and consequences.

- Coverage within a day and for sequential days, which ranged from spot samples a few times per day to 24-hour, continuous sampling.
- Collection methods that included aerosol sampling only to sampling of aerosols and gases for I-131.
- Analytical methods ranging from screening with hand-held radiation monitors to sophisticated γ-ray spectrometry systems at field locations and CONUS laboratories.

The most comprehensive set of air concentrations measurements provided full-time (24-hour) coverage for each day, used extremely high flow rates, and employed sophisticated analytical methods at collection stations, which were backed up by analytical laboratories in CONUS. These measurements were obtained at Yokota AB (D-8) and at the IMS Takasaki RN38 station and are shown in Figure 31. These two sets of air concentration measurements of Cs-134 are very consistent over time and magnitude for the two collection sites, which are approximately 41 miles apart. The reported concentrations of Cs-137 and I-131 in the same set of collections show the same consistency. Based on the quality of these results, DARWG concludes they provide a credible representation of the air concentrations in the Kanto Plain, and can serve as benchmarks for air concentrations at other locations.

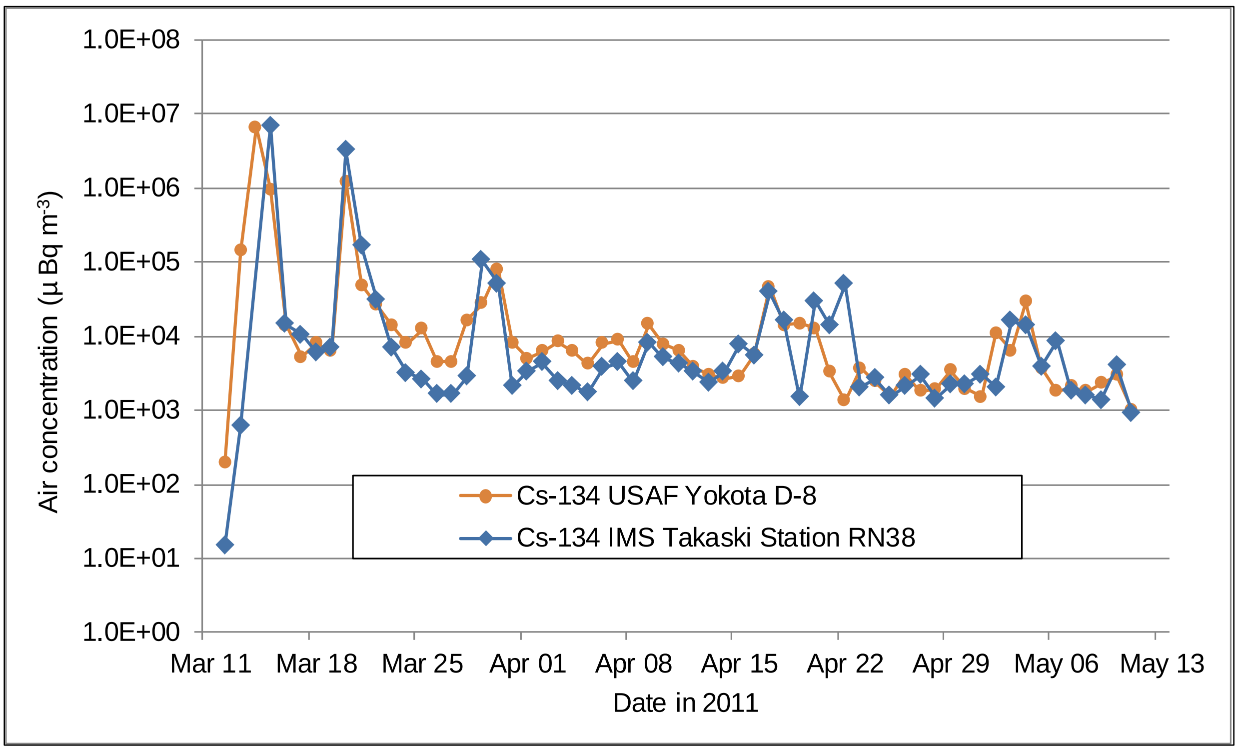


**Figure 31. Measured Cs-134 air concentration at Yokota AB (D-8) and IMS Takasaki Station RN38**

Data were not available for all days at each location as illustrated by the reported air concentration results for Yokosuka NB (D-11) in Figure 32. Measurements there were available

for March 21 through April 11, but not for every day. For days without measurements, values were derived using several methods including adjusting for radioactive decay, interpolation between measured values, direct substitution of measured data from a nearby site, or by using ratios of a nuclide with Cs-137 from a nearby site with available data.

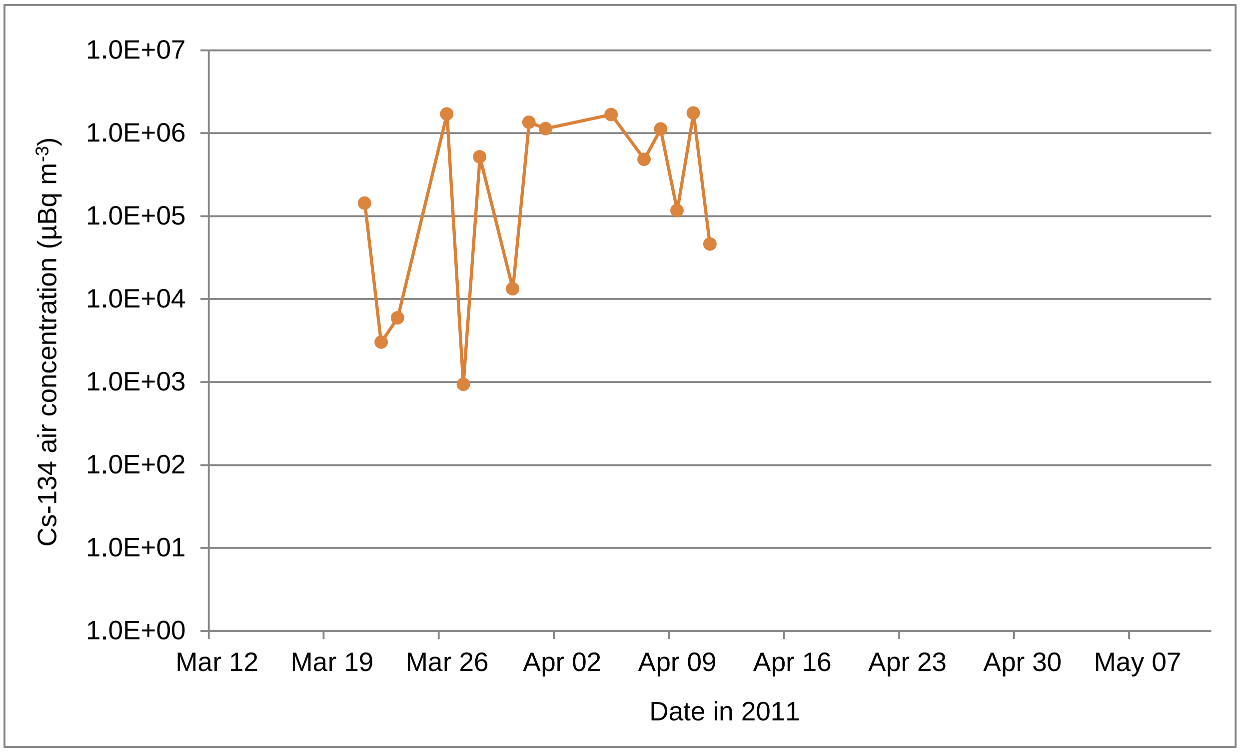


**Figure 32. Measured Cs-134 air concentrations at Yokosuka NB (D-11)**

Figure 33 illustrates the results of this process of filling gaps in measured air concentrations of Cs-134 using various techniques for Yokosuka NB (D-11). Table 32 lists the measured and derived air concentrations for all radionuclides considered at Yokosuka NB. The sources of the tabular entries are denoted by color as identified in the table's legend, and include:

- Yokota AB data that were substituted directly;
- Values from DOD measurements at Yokosuka NB;
- Values that were calculated using Cs-137 ratios;
- Values obtained using linear interpolation between values; and
- Values obtained using radioactive decay.

The concentration of Te-129m was not measured at this location; consequently an average ratio of Te-129m to Cs-137 at Yokota AB (D-8) was used as a multiplier on the daily air concentrations of Cs-137 at Yokosuka NB (D-11) to calculate the values of Te-129m. The ratios ranged in value from 0.07 to 3.23 with a CV of 84 percent.

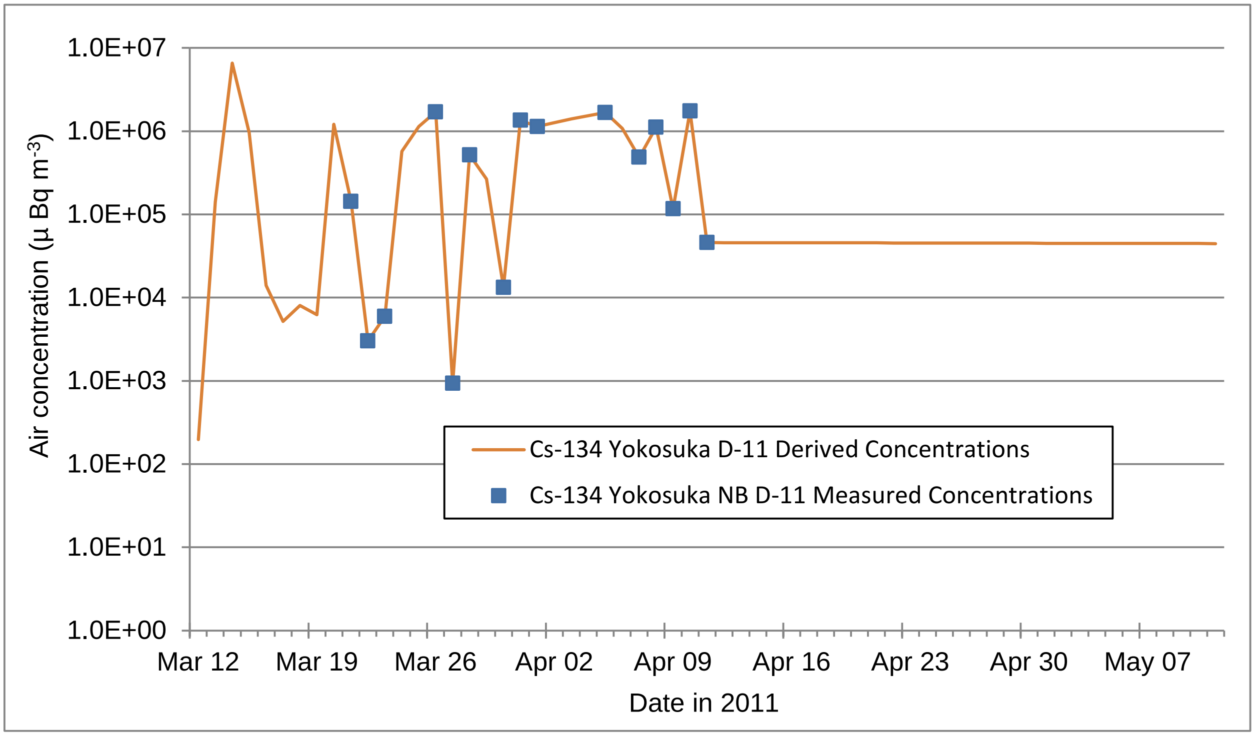


**Figure 33. Measured and derived Cs-134 air concentrations for Yokosuka NB (D-11)**

Review of these measured and derived air concentrations for all the sites raised concerns about the validity of site-specific air concentrations for the three DARWG locations Akasaka Press Center (D-9), Atsugi NAF (D-10), and Yokosuka NB (D-11) in the Kanto Plain compared with the air concentration results from sampling at Yokota AB (D-8). The three locations are 149, 160 and 165 miles southwest of the FDNPS, and Yokota AB is 142 miles southwest. These locations are shown in Figure 46. The measured air concentrations for the Kanto Plain sites differ by several orders of magnitude.

DARWG's objective was to develop reasonably conservative estimates of dose. The wide range of air concentrations for the three locations in the Kanto Plain did not seem justified for several reasons when compared to the robust Yokota AB data. These reasons include:

- The broad range did not seem reasonable considering the very similar distances and direction of all four locations from FDNPS, which would lead one to expect that the concentrations would be reasonably similar, but they were not.
- Collections of samples varied widely in time and frequency of coverage compared to the daily, 24-hour coverage at Yokota AB.
- Yokota AB results were very consistent with those from the IMS Takasaki RN38 station, which used internationally recognized collection and analytical equipment and methods.

**Table 32. Measured and derived data regions for air activity concentrations at Yokosuka NB (D-11)**

| Date (2011) | Cs-134 | Cs-136 | Cs-137 | I-131 | I-132 | I-133 | La-140 | Mo-99 | Tc-99m | Te-129 | Te-129m | Te-131m | Te-132 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Activity Concentration in Air (µBq $m^{-3}$) | | | | | | | | | | | | |
| Mar 12 | 2.0E+02 | 4.7E+01 | 2.2E+02 | 5.1E+02 | 1.5E+03 | 2.1E+02 | 1.6E+01 | 1.5E+01 | 2.8E+02 | 1.4E+02 | 2.9E+02 | 1.8E+01 | 2.5E+03 |
| Mar 13 | 1.4E+05 | 3.8E+04 | 1.5E+05 | 4.1E+05 | 8.1E+05 | 9.4E+04 | 9.6E+03 | 1.0E+04 | 7.9E+05 | 7.7E+04 | 4.7E+05 | 1.2E+04 | 1.0E+06 |
| Mar 14 | 6.6E+06 | 1.5E+06 | 6.3E+06 | 1.9E+07 | 4.5E+07 | 1.4E+06 | 3.6E+05 | 5.6E+05 | 6.3E+05 | 5.6E+04 | 6.4E+06 | 1.3E+06 | 4.8E+07 |
| Mar 15 | 9.6E+05 | 2.1E+05 | 9.8E+05 | 3.5E+06 | 4.9E+06 | 6.9E+05 | 5.0E+04 | 5.4E+04 | 4.7E+05 | 3.5E+04 | 9.3E+05 | 1.2E+05 | 5.8E+06 |
| Mar 16 | 1.4E+04 | 3.4E+03 | 2.0E+04 | 7.6E+04 | 6.3E+04 | 1.7E+03 | 1.4E+03 | 4.0E+04 | 3.2E+05 | 1.4E+04 | 2.4E+04 | 1.0E+05 | 8.9E+04 |
| Mar 17 | 5.2E+03 | 9.4E+02 | 6.1E+03 | 1.5E+04 | 1.3E+04 | 1.2E+03 | 3.1E+03 | 2.7E+04 | 1.6E+05 | 3.1E+03 | 6.6E+03 | 8.5E+04 | 1.8E+04 |
| Mar 18 | 8.0E+03 | 1.5E+03 | 9.1E+03 | 1.1E+05 | 2.7E+04 | 1.2E+03 | 4.9E+03 | 1.4E+04 | 1.3E+03 | 3.1E+03 | 9.2E+03 | 6.7E+04 | 3.4E+04 |
| Mar 19 | 6.2E+03 | 1.1E+03 | 6.6E+03 | 1.1E+05 | 1.1E+04 | 2.3E+04 | 6.6E+03 | 5.6E+02 | 7.9E+04 | 3.0E+05 | 4.7E+03 | 5.0E+04 | 1.2E+04 |
| Mar 20 | 1.2E+06 | 2.1E+05 | 1.3E+06 | 2.5E+06 | 2.0E+06 | 4.5E+04 | 8.4E+03 | 7.5E+04 | 1.6E+05 | 6.0E+05 | 9.6E+05 | 3.2E+04 | 2.3E+06 |
| Mar 21 | 1.4E+05 | 3.5E+04 | 1.8E+05 | 4.2E+05 | 2.9E+05 | 6.7E+04 | 1.3E+04 | 1.2E+04 | 2.3E+05 | 5.5E+04 | 1.2E+05 | 1.5E+04 | 3.1E+05 |
| Mar 22 | 3.0E+03 | 4.6E+03 | 1.9E+04 | 7.1E+04 | 3.2E+04 | 7.3E+03 | 1.4E+03 | 1.3E+03 | 2.5E+04 | 6.0E+03 | 1.3E+04 | 1.6E+03 | 3.4E+04 |
| Mar 23 | 5.9E+03 | 1.8E+03 | 5.7E+03 | 2.7E+04 | 9.4E+03 | 2.2E+03 | 4.2E+02 | 4.0E+02 | 7.5E+03 | 1.8E+03 | 3.9E+03 | 4.8E+02 | 1.0E+04 |
| Mar 24 | 5.7E+05 | 1.2E+03 | 6.9E+05 | 1.3E+06 | 1.1E+06 | 2.6E+05 | 5.0E+04 | 4.8E+04 | 9.0E+05 | 2.2E+05 | 4.6E+05 | 5.8E+04 | 1.2E+06 |
| Mar 25 | 1.1E+06 | 1.7E+03 | 1.4E+06 | 2.6E+06 | 2.2E+06 | 5.2E+05 | 1.0E+05 | 9.6E+04 | 1.8E+06 | 4.3E+05 | 9.2E+05 | 1.2E+05 | 2.4E+06 |
| Mar 26 | 1.7E+06 | 5.3E+02 | 2.1E+06 | 3.7E+05 | 3.4E+06 | 7.7E+05 | 1.5E+05 | 1.4E+05 | 2.7E+06 | 6.4E+05 | 1.4E+06 | 1.7E+05 | 3.6E+06 |
| Mar 27 | 9.3E+02 | 4.0E+02 | 3.1E+02 | 1.0E+04 | 5.0E+02 | 1.1E+02 | 2.2E+01 | 2.1E+01 | 4.0E+02 | 9.5E+01 | 2.1E+02 | 2.6E+01 | 5.3E+02 |
| Mar 28 | 5.2E+05 | 1.1E+03 | 5.2E+05 | 1.9E+06 | 8.5E+05 | 1.9E+05 | 3.8E+04 | 3.6E+04 | 6.8E+05 | 1.6E+05 | 3.5E+05 | 4.3E+04 | 9.0E+05 |
| Mar 29 | 2.7E+05 | 2.0E+03 | 5.1E+03 | 1.0E+04 | 8.4E+03 | 1.9E+03 | 3.7E+02 | 3.6E+02 | 6.7E+03 | 1.6E+03 | 3.4E+03 | 4.3E+02 | 8.9E+03 |
| Mar 30 | 1.3E+04 | 4.8E+03 | 1.2E+04 | 2.3E+04 | 1.9E+04 | 4.4E+03 | 8.6E+02 | 8.2E+02 | 1.5E+04 | 3.7E+03 | 7.9E+03 | 9.9E+02 | 2.0E+04 |
| Mar 31 | 1.4E+06 | 6.0E+02 | 1.4E+06 | 1.0E+06 | 2.4E+06 | 5.5E+05 | 1.1E+05 | 1.0E+05 | 1.9E+06 | 4.5E+05 | 9.7E+05 | 1.2E+05 | 2.5E+06 |
| Apr 1 | 1.1E+06 | 3.9E+02 | 7.1E+06 | 4.0E+05 | 1.2E+07 | 2.7E+06 | 5.2E+05 | 4.9E+05 | 9.3E+06 | 2.2E+06 | 4.8E+06 | 6.0E+05 | 1.2E+07 |

Source of Air Concentration Value

Yokota AB data directly substituted — Calculation using Cs-137 ratios

DOD measurement at Yokosuka NB — Linear interpolation between adjacent values — Decay adjusted

Table 32. Measured and derived data regions for air activity concentrations at Yokosuka NB (D-11) (cont.)

| Date (2011) | Cs-134 | Cs-136 | Cs-137 | I-131 | I-132 | I-133 | La-140 | Mo-99 | Tc-99m | Te-129 | Te-129m | Te-131m | Te-132 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Activity Concentration in Air (µBq $m^{-3}$) | | | | | | | | | | | | |
| Apr 2 | 1.3E+06 | 5.0E+02 | 5.5E+06 | 4.0E+05 | 9.0E+06 | 2.1E+06 | 4.0E+05 | 3.8E+05 | 7.2E+06 | 1.7E+06 | 3.7E+06 | 4.6E+05 | 9.5E+06 |
| Apr 3 | 1.4E+06 | 5.0E+02 | 3.9E+06 | 4.0E+05 | 6.3E+06 | 1.5E+06 | 2.8E+05 | 2.7E+05 | 5.1E+06 | 1.2E+06 | 2.6E+06 | 3.2E+05 | 6.7E+06 |
| Apr 4 | 1.5E+06 | 4.4E+02 | 2.2E+06 | 4.1E+05 | 3.7E+06 | 8.4E+05 | 1.6E+05 | 1.6E+05 | 2.9E+06 | 7.0E+05 | 1.5E+06 | 1.9E+05 | 3.9E+06 |
| Apr 5 | 1.7E+06 | 3.0E+02 | 6.2E+05 | 4.1E+05 | 1.0E+06 | 2.3E+05 | 4.5E+04 | 4.3E+04 | 8.2E+05 | 1.9E+05 | 4.2E+05 | 5.2E+04 | 1.1E+06 |
| Apr 6 | 1.1E+06 | 4.1E+02 | 5.5E+05 | 5.2E+05 | 8.9E+05 | 2.1E+05 | 4.0E+04 | 3.8E+04 | 7.2E+05 | 1.7E+05 | 3.7E+05 | 4.6E+04 | 9.5E+05 |
| Apr 7 | 4.8E+05 | 4.4E+02 | 4.7E+05 | 6.4E+05 | 7.7E+05 | 1.8E+05 | 3.4E+04 | 3.3E+04 | 6.2E+05 | 1.5E+05 | 3.2E+05 | 3.9E+04 | 8.2E+05 |
| Apr 8 | 1.1E+06 | 2.6E+02 | 1.4E+06 | 1.0E+06 | 2.2E+06 | 5.1E+05 | 9.9E+04 | 9.5E+04 | 1.8E+06 | 4.2E+05 | 9.1E+05 | 1.1E+05 | 2.4E+06 |
| Apr 9 | 1.2E+05 | 5.3E+02 | 1.3E+05 | 2.1E+05 | 2.1E+05 | 4.9E+04 | 9.6E+03 | 9.1E+03 | 1.7E+05 | 4.1E+04 | 8.8E+04 | 1.1E+04 | 2.3E+05 |
| Apr 10 | 1.7E+06 | 3.1E+02 | 5.6E+05 | 1.2E+05 | 9.1E+05 | 2.1E+05 | 4.1E+04 | 3.9E+04 | 7.3E+05 | 1.7E+05 | 3.8E+05 | 4.7E+04 | 9.7E+05 |
| Apr 11 | 4.6E+04 | 3.1E+02 | 6.0E+04 | 4.4E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 12 | 4.6E+04 | 2.9E+02 | 6.0E+04 | 4.1E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 13 | 4.6E+04 | 2.8E+02 | 6.0E+04 | 3.7E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 14 | 4.6E+04 | 2.7E+02 | 6.0E+04 | 3.4E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 15 | 4.6E+04 | 2.5E+02 | 6.0E+04 | 3.1E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 16 | 4.6E+04 | 2.4E+02 | 6.0E+04 | 2.9E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 17 | 4.6E+04 | 2.3E+02 | 6.0E+04 | 2.6E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 18 | 4.6E+04 | 2.2E+02 | 6.0E+04 | 2.4E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 19 | 4.6E+04 | 2.1E+02 | 6.0E+04 | 2.2E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 20 | 4.5E+04 | 2.0E+02 | 6.0E+04 | 2.0E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 21 | 4.5E+04 | 1.9E+02 | 6.0E+04 | 1.9E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 22 | 4.5E+04 | 1.8E+02 | 6.0E+04 | 1.7E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |

Source of Air Concentration Value
Yokota AB data directly substituted | Calculation using Cs-137 ratios
DOD measurement at Yokosuka NB | Linear interpolation between adjacent values | Decay adjusted

**Table 32. Measured and derived data regions for air activity concentrations at Yokosuka NB (D-11) (cont.)**

| Date (2011) | Cs-134 | Cs-136 | Cs-137 | I-131 | I-132 | I-133 | La-140 | Mo-99 | Tc-99m | Te-129 | Te-129m | Te-131m | Te-132 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Activity Concentration in Air (µBq $m^{-3}$) | | | | | | | | | | | | |
| Apr 23 | 4.5E+04 | 1.7E+02 | 6.0E+04 | 1.6E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 24 | 4.5E+04 | 1.6E+02 | 6.0E+04 | 1.4E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 25 | 4.5E+04 | 1.5E+02 | 6.0E+04 | 1.3E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 26 | 4.5E+04 | 1.4E+02 | 6.0E+04 | 1.2E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 27 | 4.5E+04 | 1.4E+02 | 6.0E+04 | 1.1E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 28 | 4.5E+04 | 1.3E+02 | 6.0E+04 | 1.0E+04 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 29 | 4.5E+04 | 1.2E+02 | 6.0E+04 | 9.4E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| Apr 30 | 4.5E+04 | 1.2E+02 | 5.9E+04 | 8.6E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 1 | 4.5E+04 | 1.1E+02 | 5.9E+04 | 7.9E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 2 | 4.5E+04 | 1.1E+02 | 5.9E+04 | 7.3E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 3 | 4.5E+04 | 1.0E+02 | 5.9E+04 | 6.7E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 4 | 4.5E+04 | 9.6E+01 | 5.9E+04 | 6.1E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 5 | 4.5E+04 | 9.2E+01 | 5.9E+04 | 5.6E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 6 | 4.5E+04 | 8.7E+01 | 5.9E+04 | 5.1E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 7 | 4.5E+04 | 8.3E+01 | 5.9E+04 | 4.7E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 8 | 4.5E+04 | 7.9E+01 | 5.9E+04 | 4.3E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 9 | 4.5E+04 | 7.5E+01 | 5.9E+04 | 4.0E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 10 | 4.5E+04 | 7.1E+01 | 5.9E+04 | 3.6E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |
| May 11 | 4.5E+04 | 6.8E+01 | 5.9E+04 | 3.3E+03 | 9.7E+04 | 2.2E+04 | 4.3E+03 | 4.1E+03 | 7.8E+04 | 1.9E+04 | 4.0E+04 | 5.0E+03 | 1.0E+05 |

Source of Air Concentration Value

Yokota AB data directly substituted — Calculation using Cs-137 ratios

DOD measurement at Yokosuka NB — Linear interpolation between adjacent values — Decay adjusted

Consequently, DARWG believed that substitution of Yokota AB results, with possible adjustment for external dose rates was preferable because it would provide data with full-time coverage and superior sensitivity and uncertainty. To evaluate the possible effects of this approach, DARWG calculated the effective dose and thyroid dose for each location using the location-specific measured and derived air concentrations, and repeated the calculations using Yokota AB air concentrations. The doses calculated using the site specific air concentrations were greater than those calculated using air concentrations based on the Yokota AB measurements. Nevertheless, DARWG concludes that use of the Yokota AB air concentrations results in doses that are based on more comprehensive coverage of the entire 60-day exposure period and have less uncertainty.

Figure 34 displays air concentrations for Cs-134 at Misawa AB (D-1), Sendai Airport (D-2), and City of Ishinomaki (D-3). Measured concentrations are shown by discrete points and calculated concentrations by the solid lines. These locations are 228, 50, and 72 miles northeast of the FDNPS. The measured values for Sendai Airport and the City of Ishinomaki show some correlation to each other and are about the same order of magnitude, which is reasonable because the two locations are within 20 miles of each other. The Misawa AB measurements are about four orders of magnitude lower that either the Sendai Airport or City of Ishinomaki measurements, which makes sense since Misawa AB is about 150 miles farther north from the FDNPS.

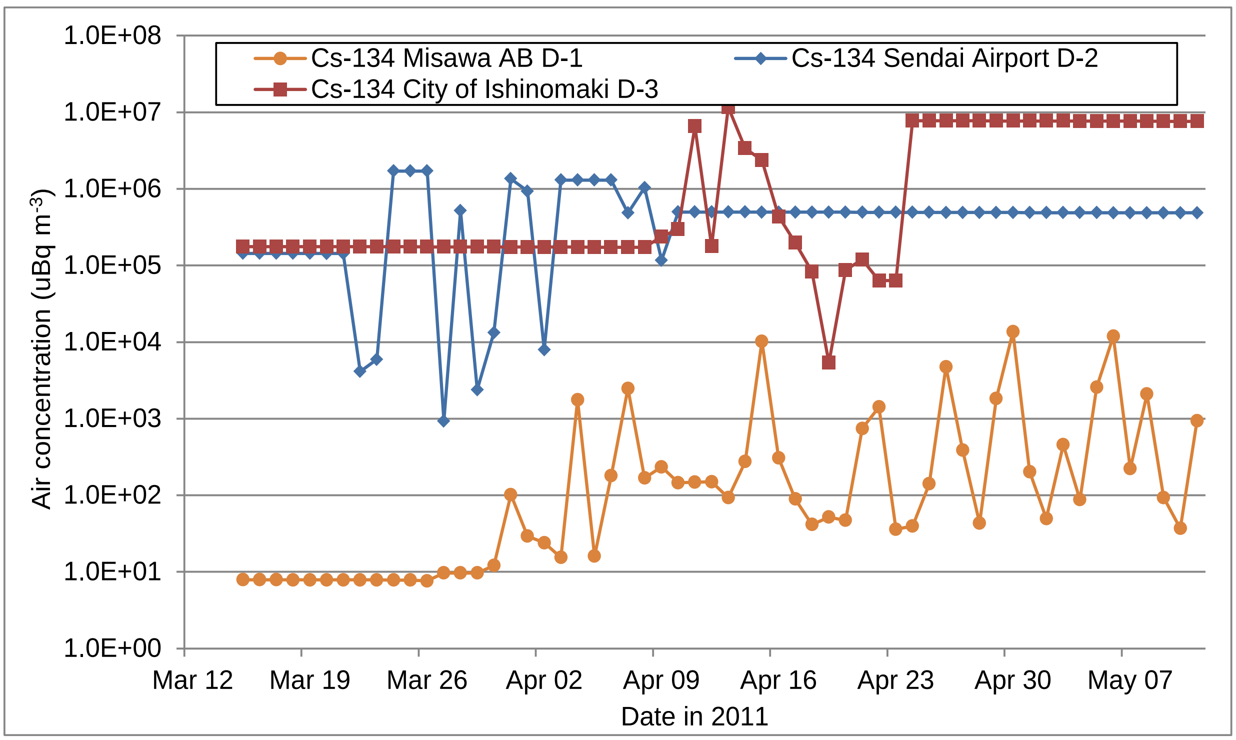


**Figure 34. Cs-134 air concentrations at Misawa AB (D-1), Sendai Airport (D-2) and City of Ishinomaki (D-3)**

5.2.3. Drinking Water

Drinking water concentration data for selected radionuclides were available for 11 DARWG locations from the MEXT stations in the same prefecture and for the IMS. Of the 11 locations, five had measured drinking water concentrations below the MDA. Figure 35 through Figure 40 show the water concentrations for each location that had values greater than the MDA. Iodine-131 was the only radionuclide with results greater than the MDA at Atsugi NAF (D-10) and Yokosuka NB (D-11). Unlike air concentrations, gaps in water concentration results were not calculated (i.e., by decay, interpolation, substitution, or using cesium ratios for other days or other nuclides) because blank table entries were actually measured values that were less than MDA. This was not the same case with air concentrations because they were not measured every day and the missing values had to be estimated.

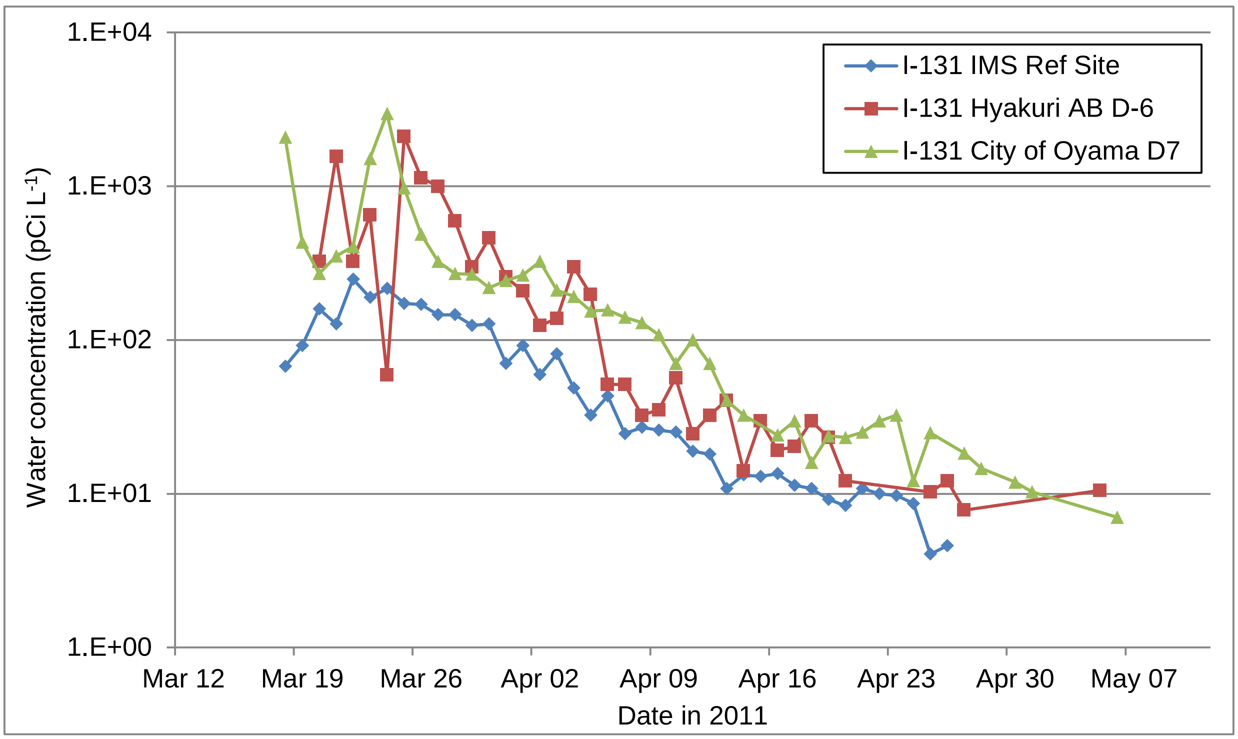


**Figure 35. I-131 daily drinking water concentration at IMS, Hyakuri AB (D-6) and City of Oyama (D-7)**

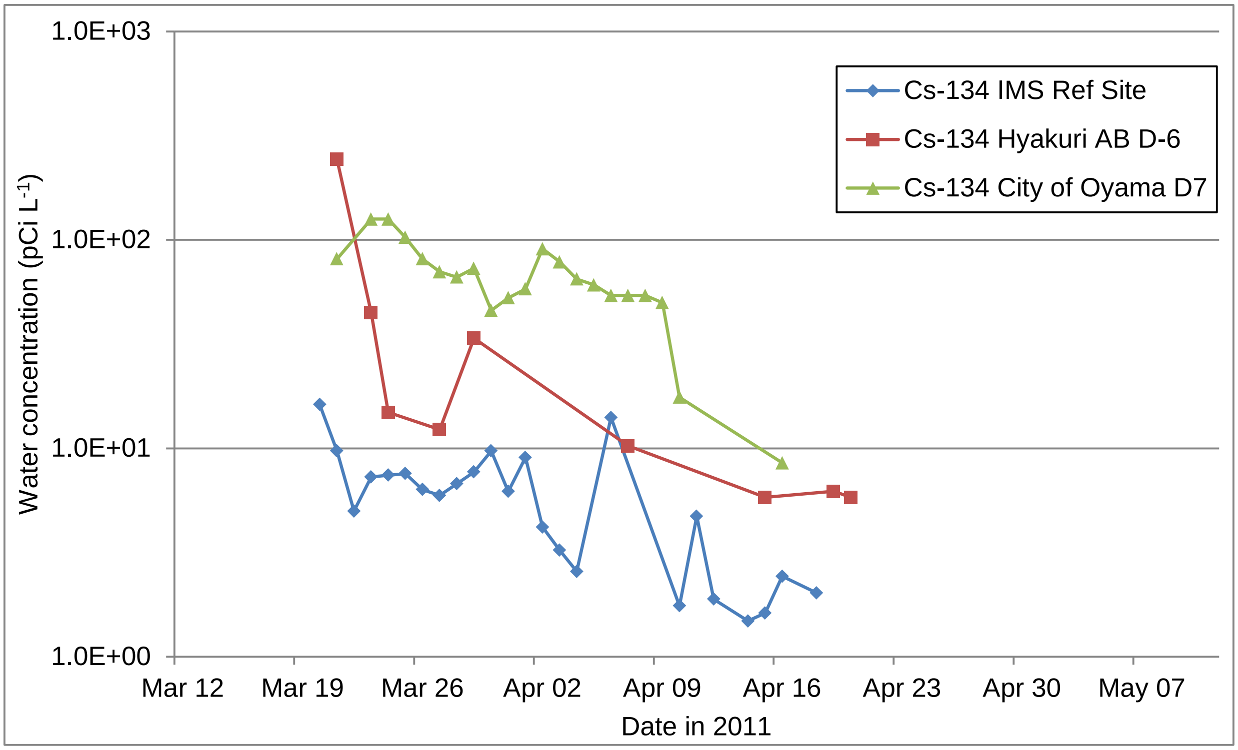


**Figure 36. Cs-134 daily drinking water concentrations at IMS, Hyakuri AB (D-6) and City of Oyama (D-7)**

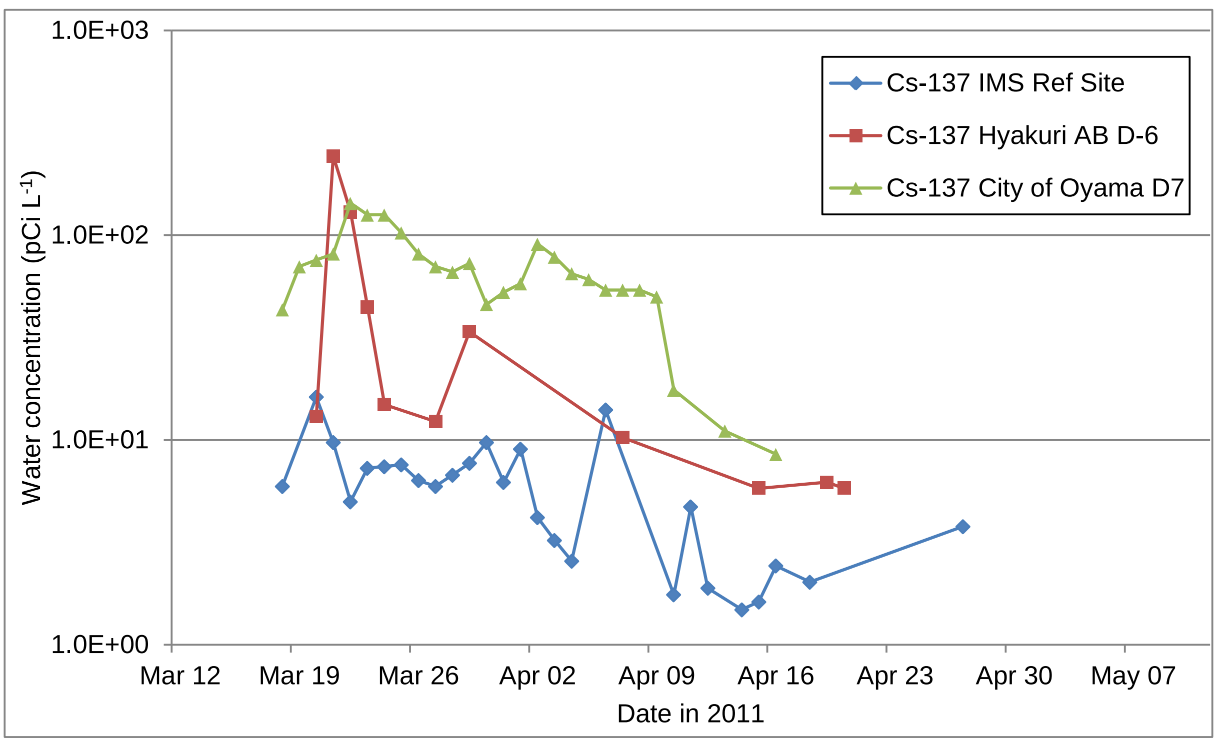


**Figure 37. Cs-137 daily drinking water concentration at IMS, Hyakuri AB (D-6) and City of Oyama (D-7)**

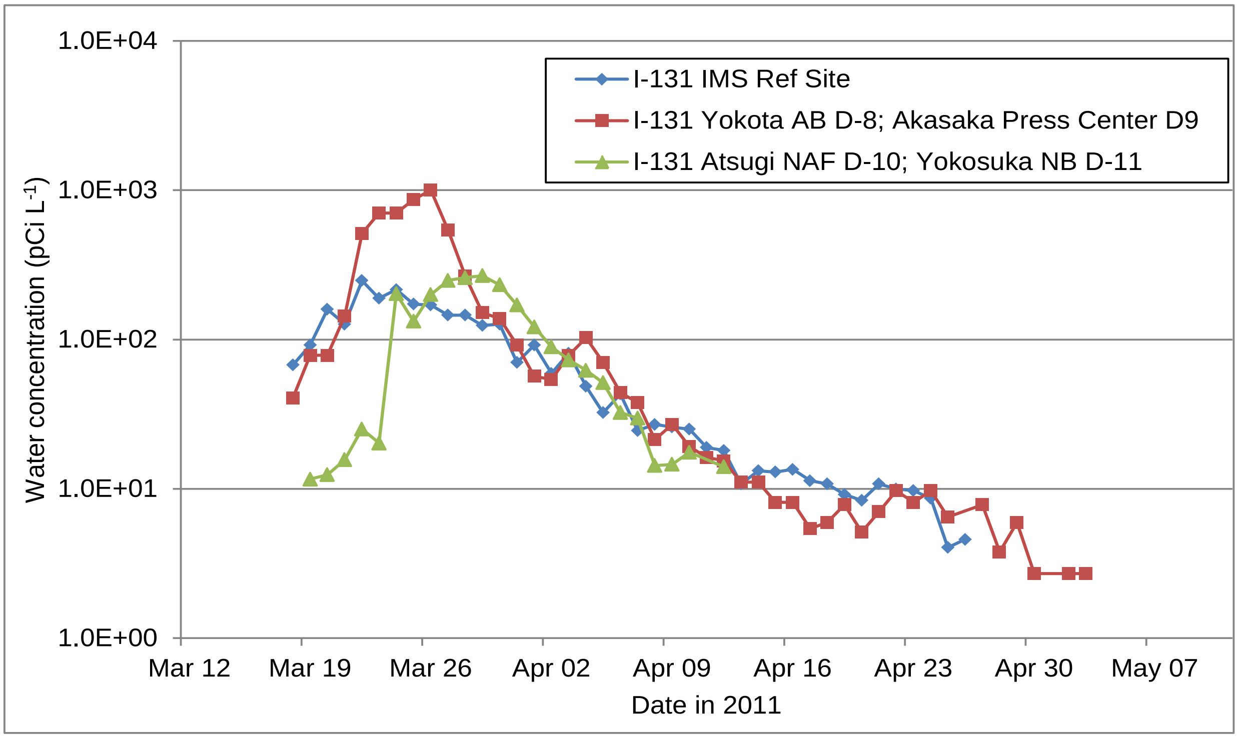


**Figure 38. I-131 daily drinking water concentration at IMS, and locations D-8, D-9, D-10, and D-11**

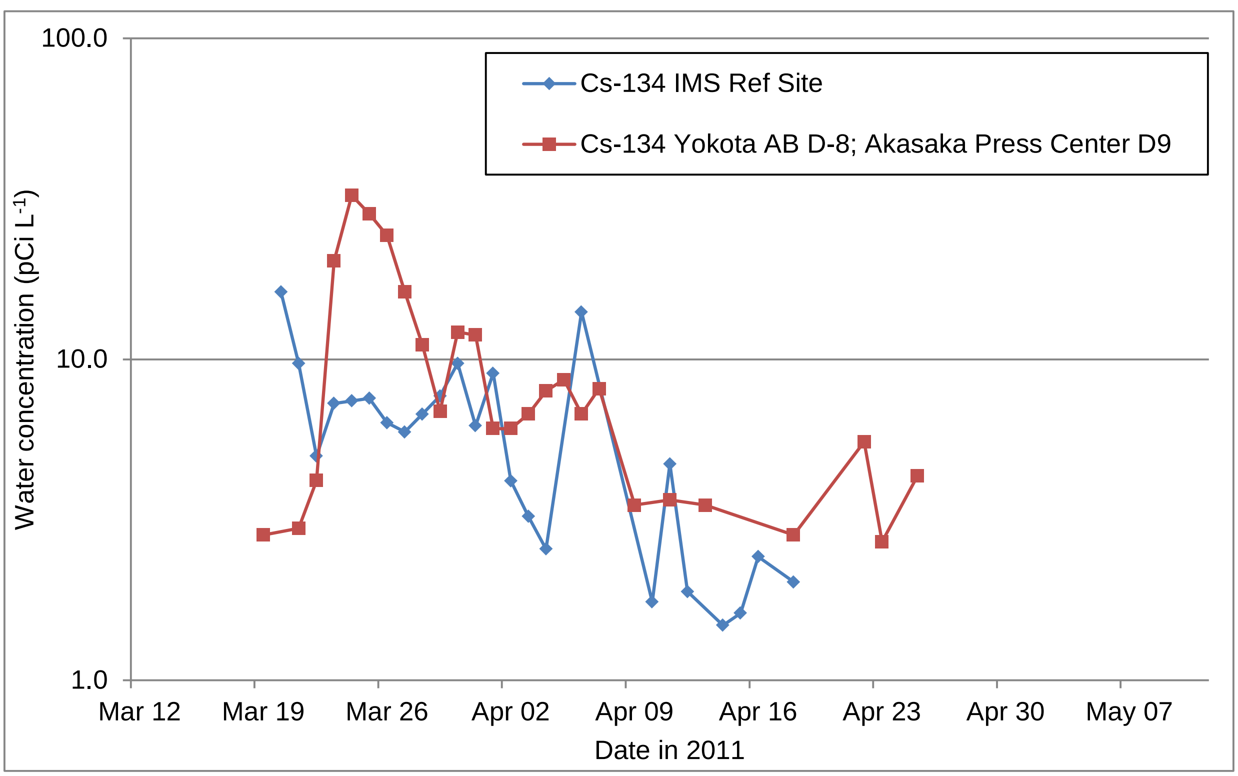


**Figure 39. Cs-134 daily drinking water concentration at IMS, and locations D-8 and D-9**

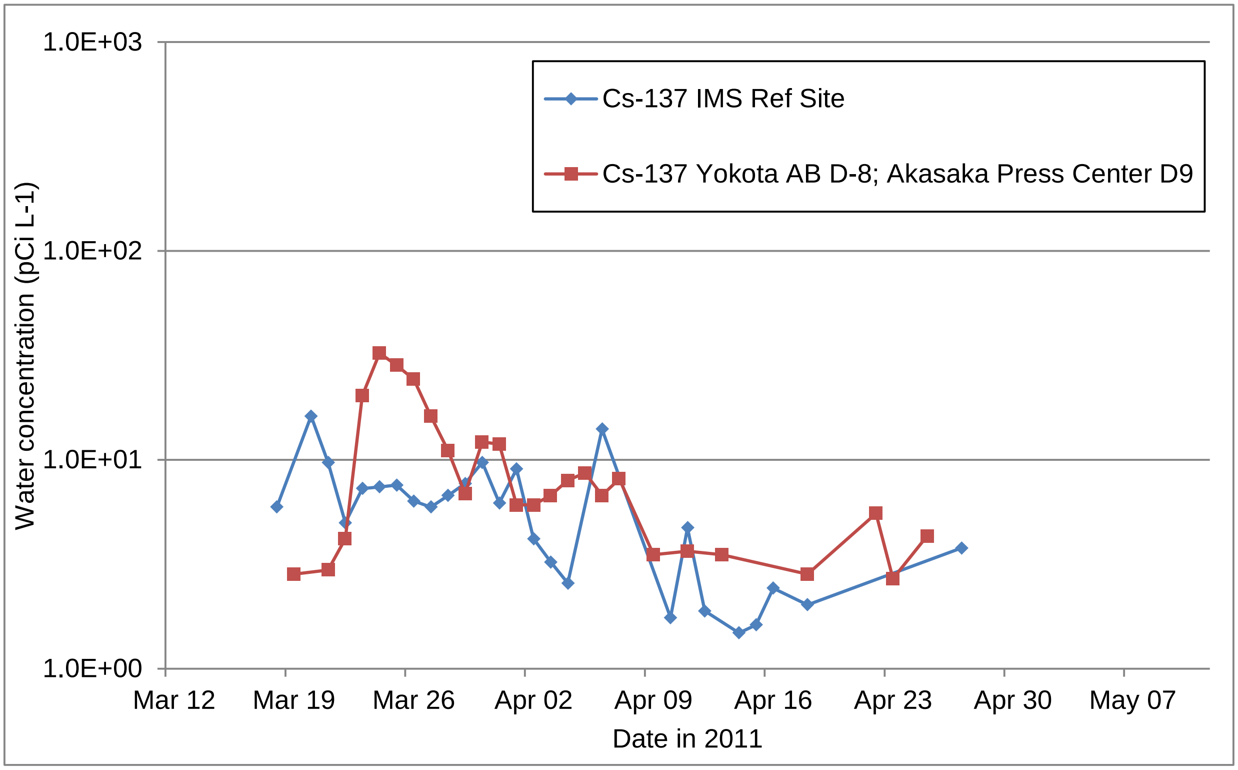


**Figure 40. Cs-137 daily drinking water concentration at IMS, and locations D-8 and D-9**

5.2.4. Soil

As shown in Table 25, soil concentration data were available from DOD for five DARWG locations. Figure 41 through Figure 45 shows the soil concentration data graphically. From the shapes and smoothness of the graphs in this figure it is obvious that much of the soil data had to be constructed from a limited number of measured data. The acquisition and construction of the soil data set are discussed in Section 2.6.

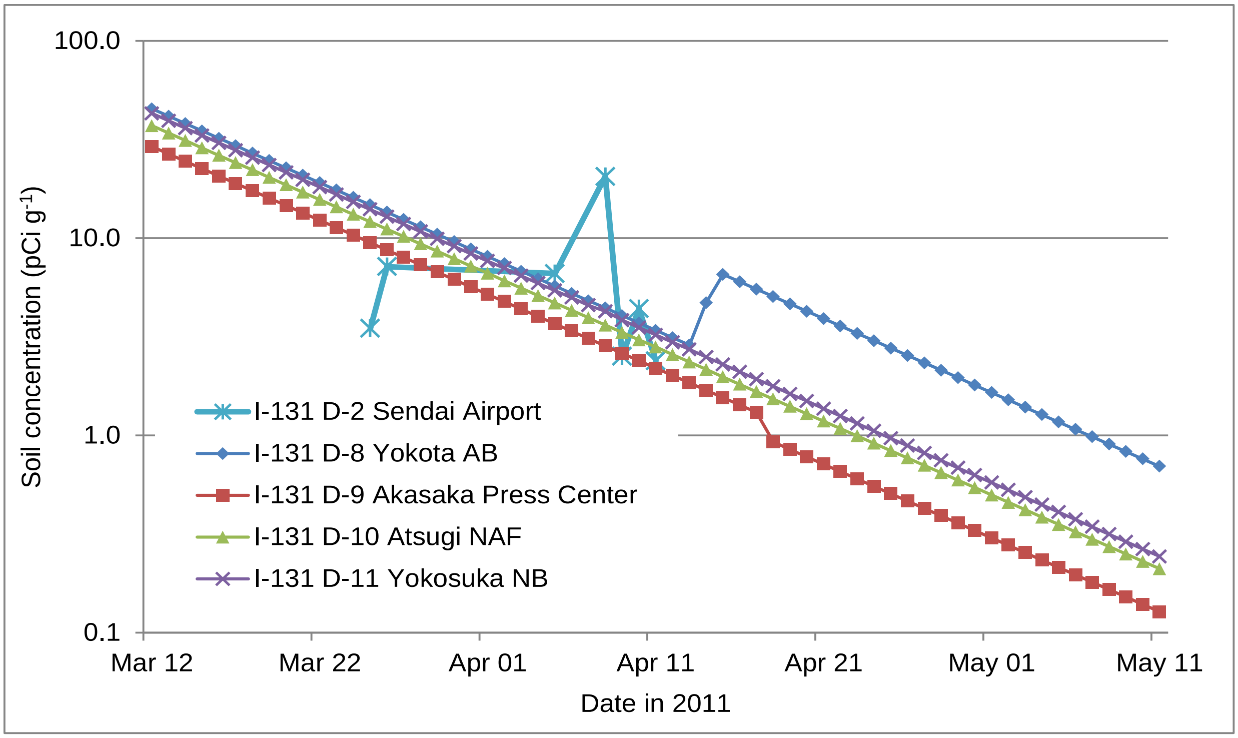


**Figure 41. I-131 soil concentrations used in dose calculations**

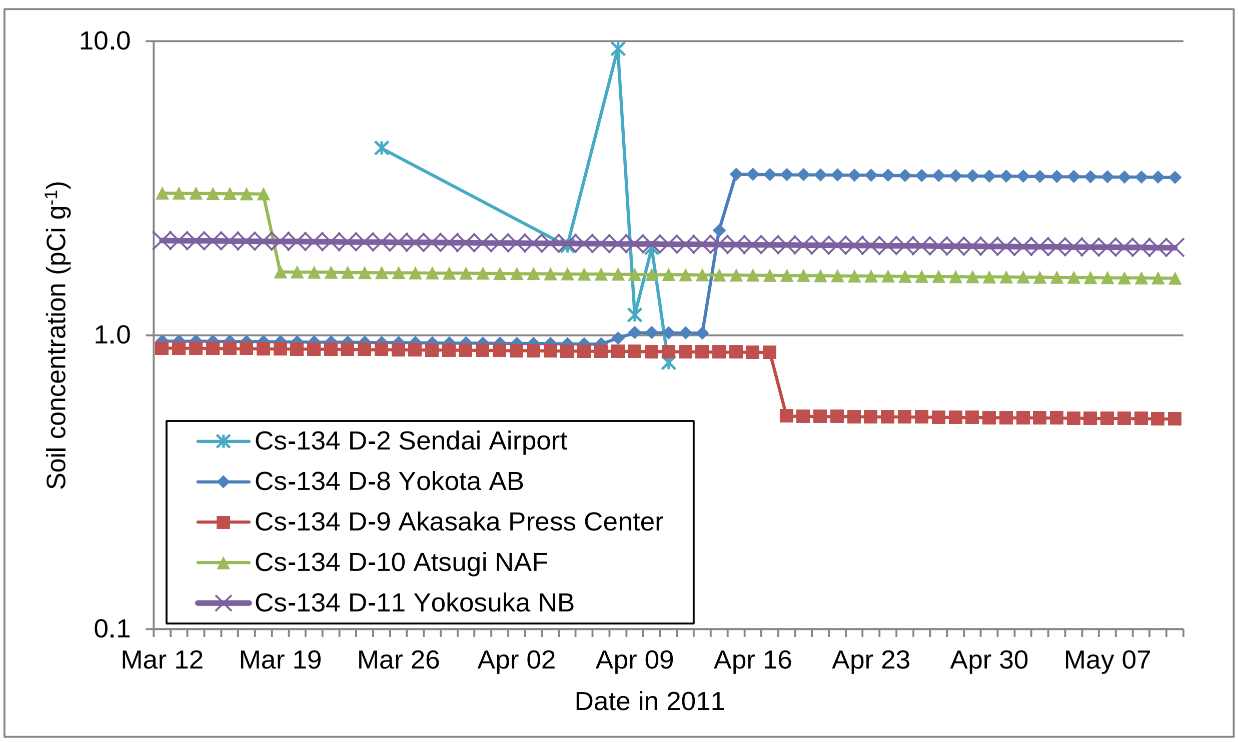


**Figure 42. Cs-134 soil concentrations used in dose calculations**

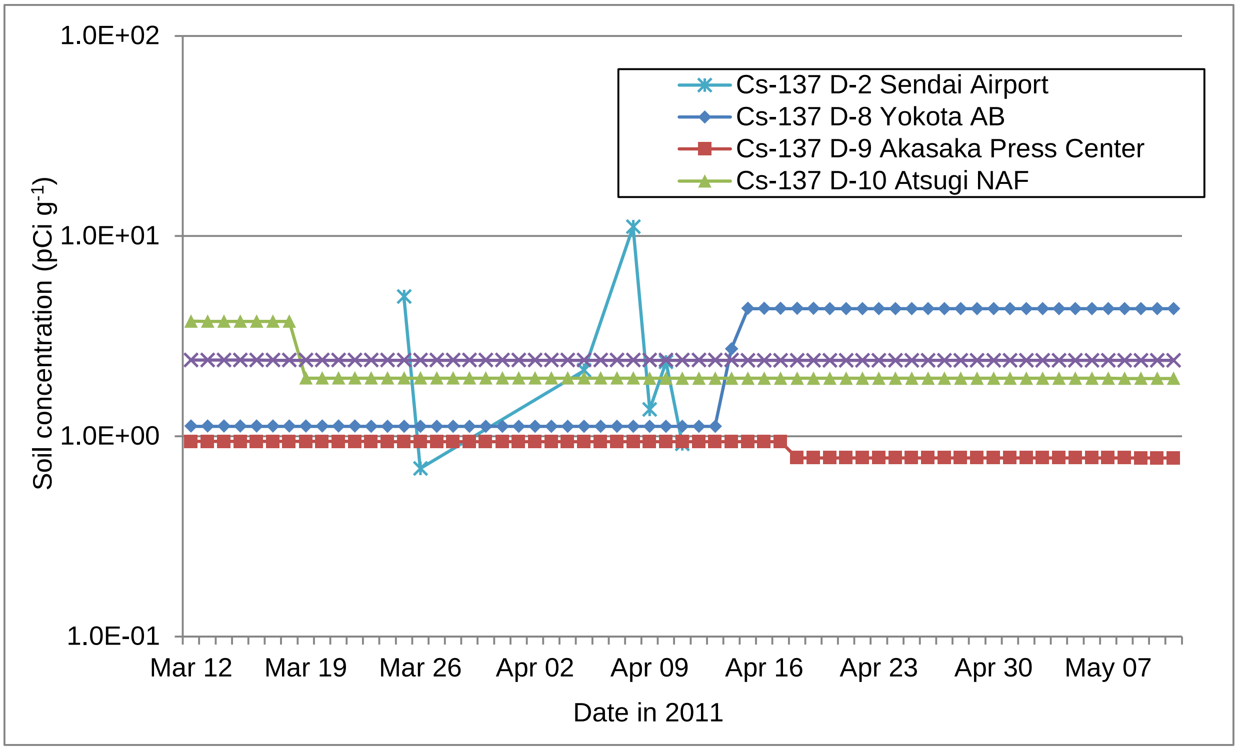


**Figure 43. Cs-137 soil concentrations used in dose calculations**

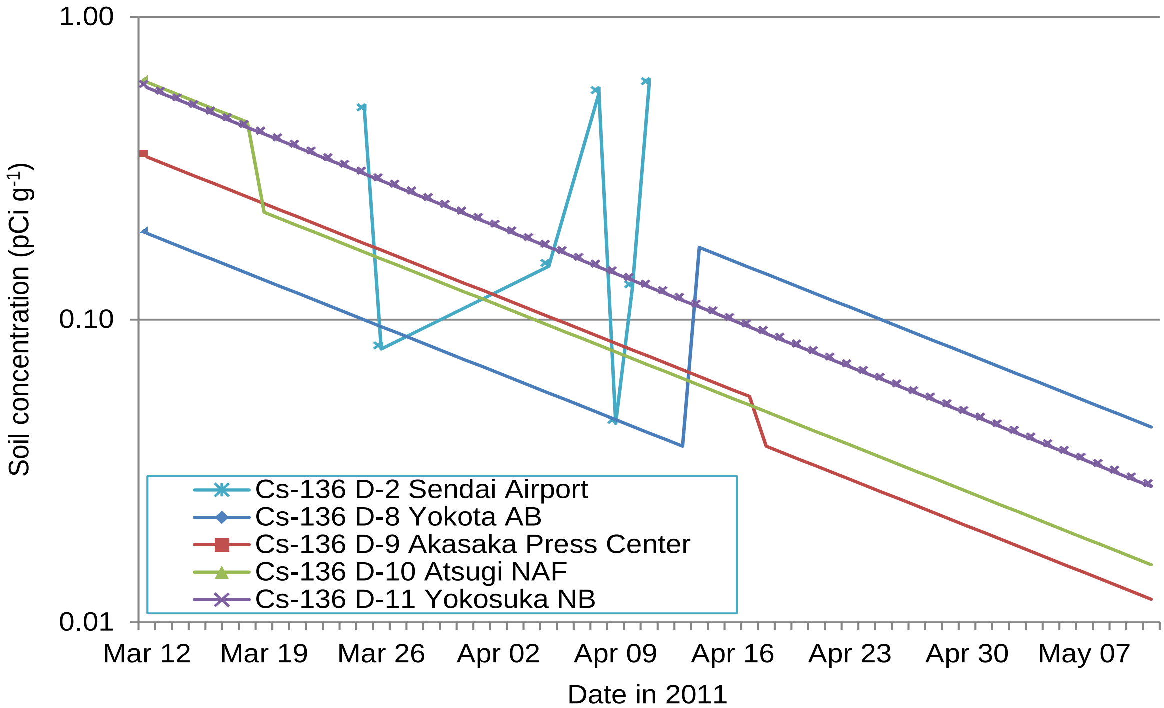


**Figure 44. Cs-136 soil concentrations used in dose calculations**

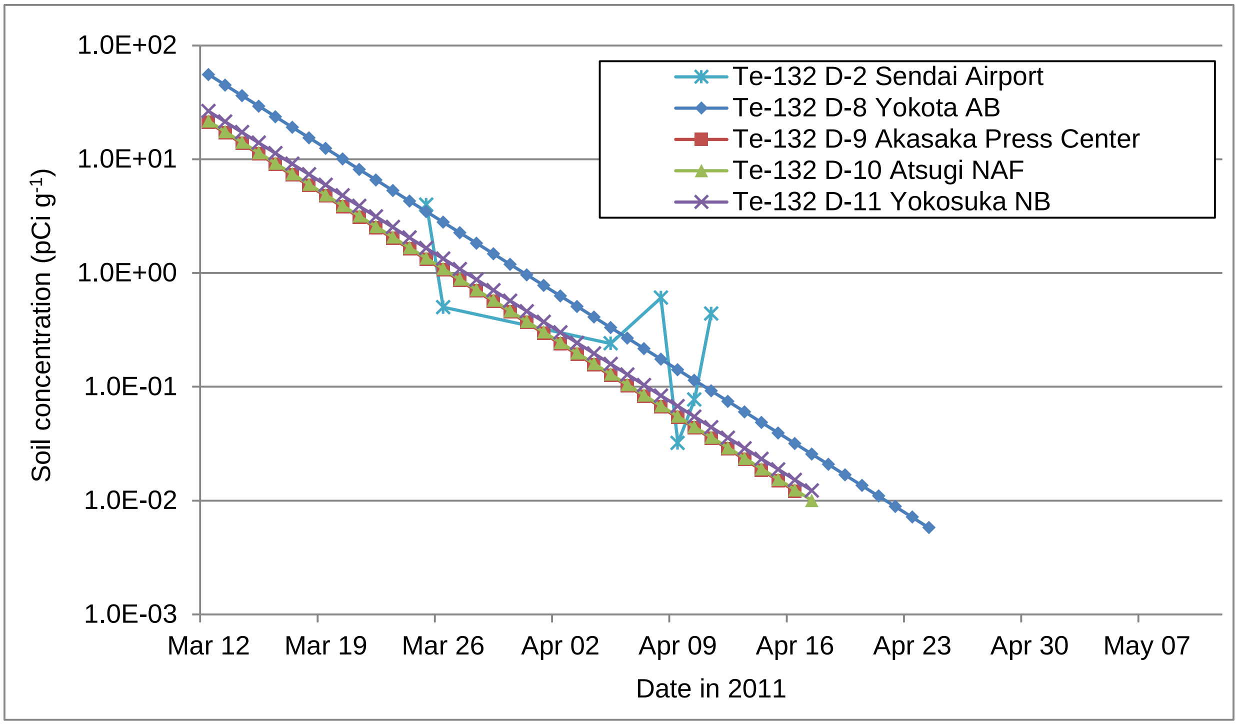


**Figure 45. Te-132 soil concentrations used in dose calculations**

### 5.3 Dependence of Dose on Distance

It is useful in analyzing the results to group certain DARWG sites that are geographically similar by direction, distance, and topography. Figure 46 through Figure 49 show DARWG locations D-1 to D-4, D-5 to D-7, D-8 to D-12, and D-13 to D-14 with the whole body effective doses for adults with the highest activities and outdoor time (humanitarian relief, PEP Category 2). The results for locations at similar distances are consistent with each other and results at different distance trend as expected with locations at greater distances having smaller doses.

City of Yamagata (D-4), Sendai Airport (D-2), and City of Ishinomaki (D-3), are 69, 50, and 72 miles northwest to northeast from the FDNPS, and have whole body effective doses of 0.036, 0.12, and 0.079 rem (0.36, 1.2, and 0.79 mSv). Misawa AB (D-1) is about 150 miles further north and shows a lower whole body effective dose of 0.006 rem (0.06 mSv), which as expected is almost all derived from external radiation sources.

IMS Takasaki Station RN38, City of Oyama (D-7) and Hyakuri AB (D-6) are 133, 102, and 92 miles from southwest to southeast from the FDNPS and show whole body effective doses of 0.038, 0.087, and 0.075 rem (0.38, 0.87, and 0.75 mSv). External dose contributes 0.031, 0.025, and 0.023 rem (0.31, 0.25, and 0.23 mSv) to the total doses.

Yokota AB (D-8), Atsugi NAF (D-10), and Akasaka Press Center (D-9) are 149, 160, and 142 miles southwest to southeast from the FDNPS and show whole body effective doses of 0.055, 0.039, and 0.046 rem (0.55, 0.39, and 0.46 mSv). External radiation contributes 74 percent, 70 percent, and 66 percent of the total doses.

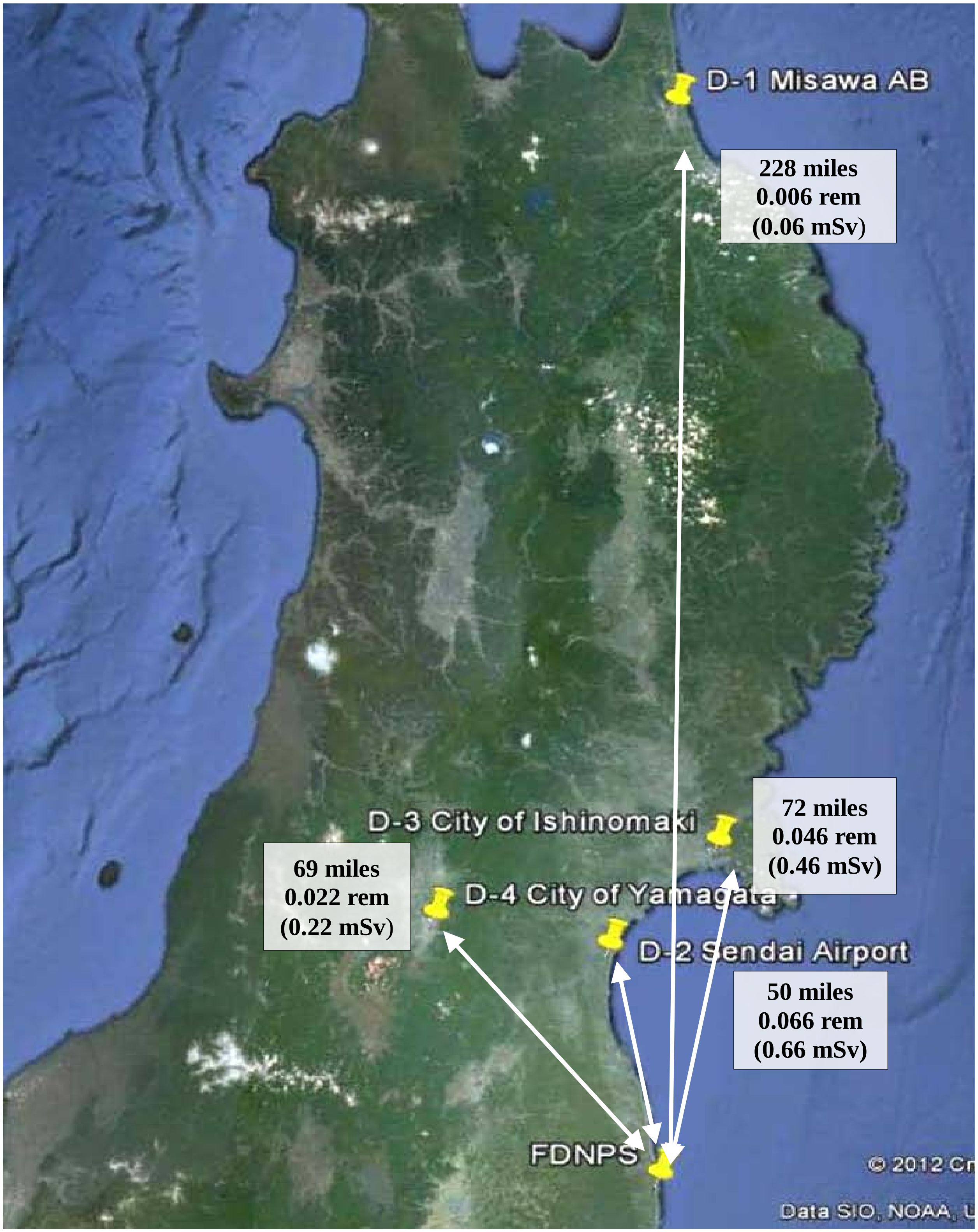


**Figure 46. Locations, distances, and whole body effective doses for DARWG locations D-1 through D-4**

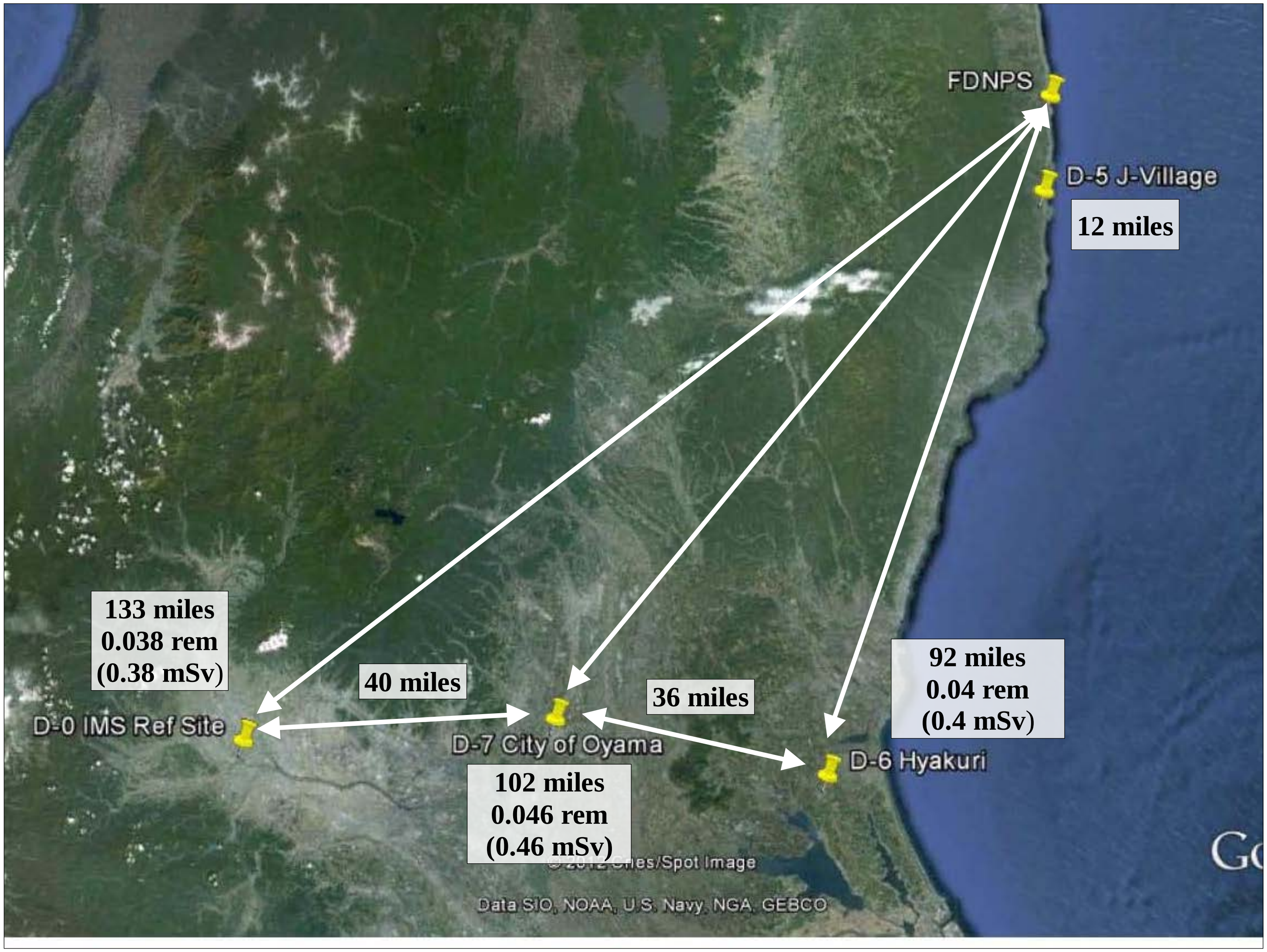


**Figure 47. Locations, distances, and whole body effective doses for DARWG locations D-5 through D-7**

Camp Fuji (D-12) at 189 miles southwest and Yokosuka NB (D-11) at 165 miles south southwest have whole body effective doses of 0.015 and 0.033 rem (0.15 and 0.33 mSv). External radiation contributes 66 percent and 62 percent of the total dose.

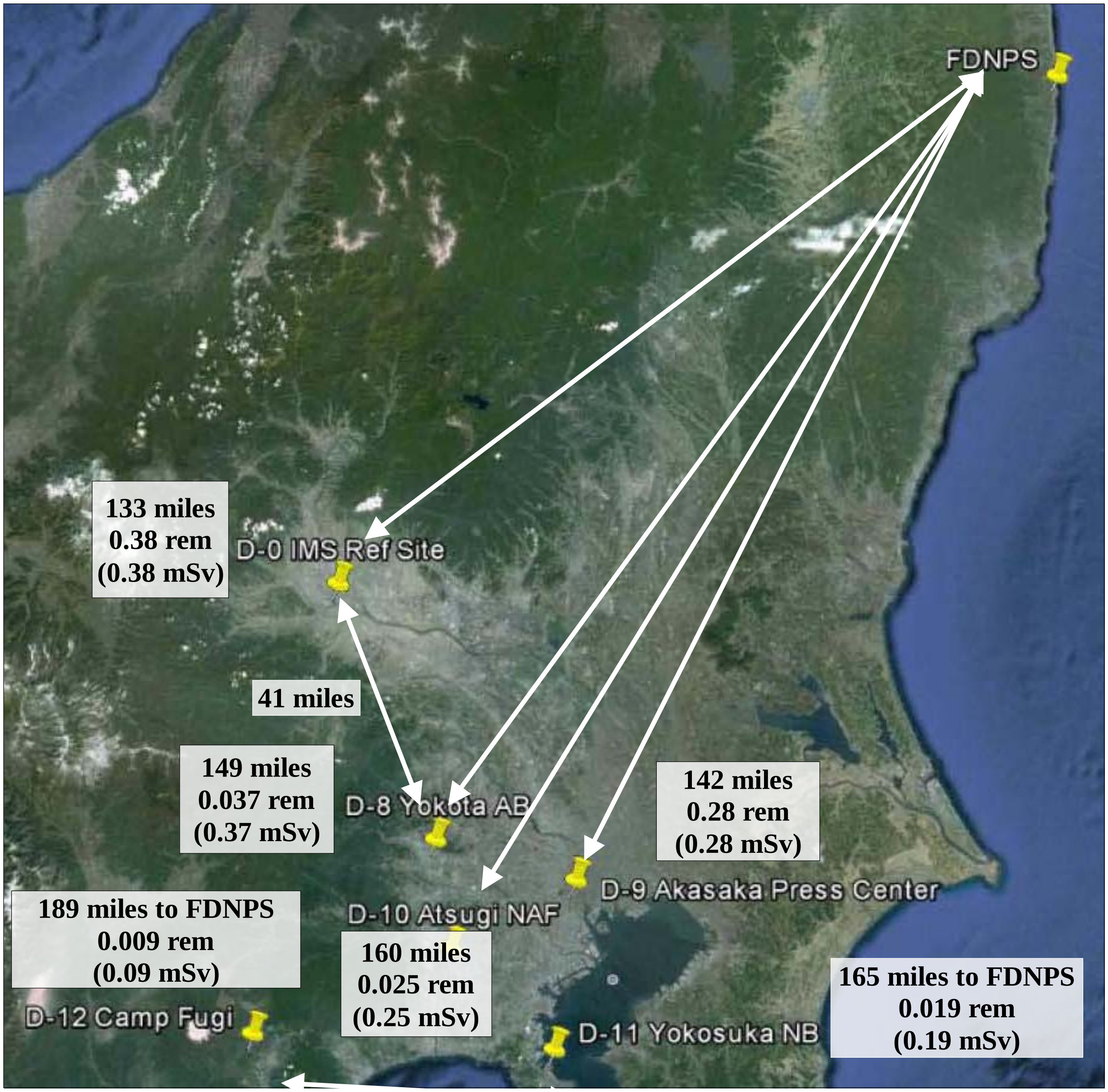


**Figure 48. Locations, distances, and whole body effective doses for DARWG locations D-8 through D-12**

The DARWG locations that are the farthest from the FDNPS are Iwakuni MCAS (D-13) at 542 miles and Sasebo NB (D-14) at 702 miles southwest, which showed essentially no measurable increase in external radiation dose rate above the pre-incident values at 0.002 and 0.003 rem (0.02 and 0.03 mSv).

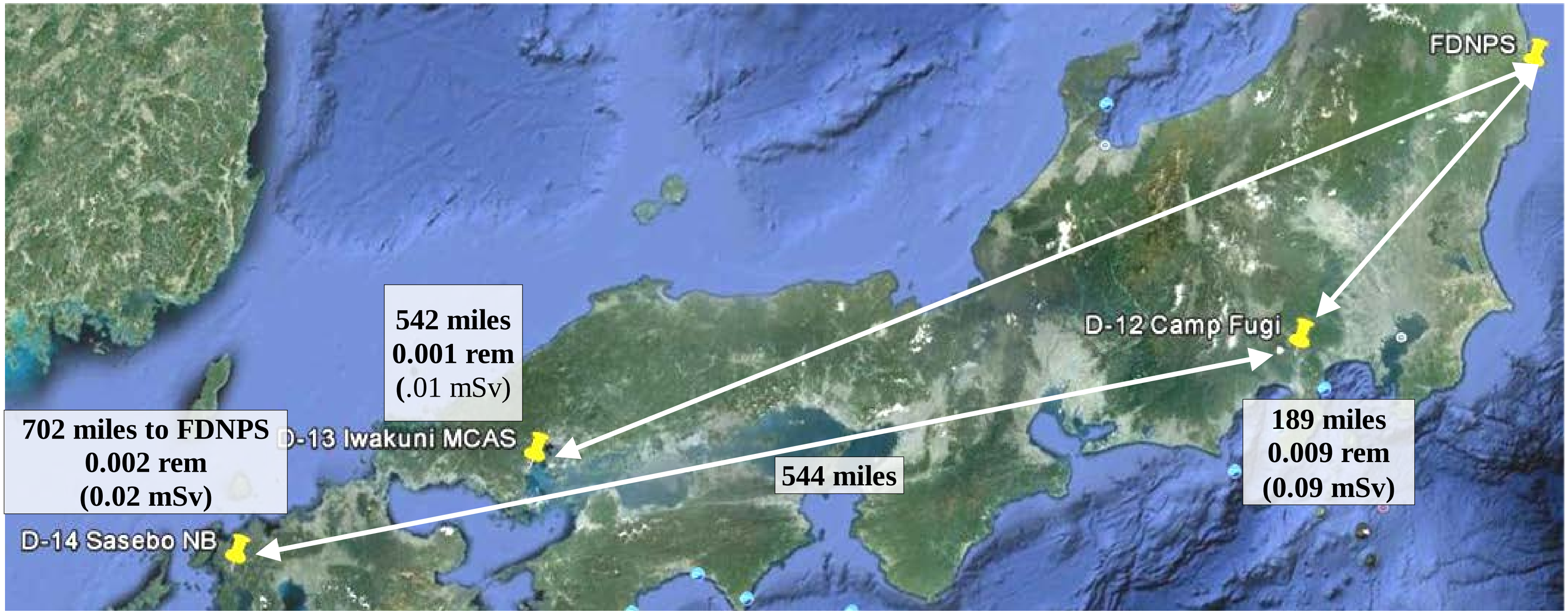


**Figure 49. Locations, distances, and whole body effective doses for DARWG locations D-13 through D-14**

## 5.4 Dependence of Dose on Time

Figure 50 through Figure 57 display the time dependence of whole body effective and thyroid doses for the PEP category 2, adults, humanitarian relief at Yokota AB (D-8). About 70 percent of the whole body effective dose is obtained in the first 30 days, but thyroid dose is accumulated more quickly with 70 percent in 13 days. At about 30 days the thyroid dose is at 93 percent of the estimated maximum. This shows that most of the internal dose was received in the first few weeks corresponding to the timing of the major releases of radioactivity, whereas the external dose was slower to accumulate and became more of a contributor after the major plumes had been released and their radioactive materials had dispersed or decayed to lower levels. In addition, the contribution of external radiation to whole body effective dose is about three times the contribution from internal inhalation and ingestion; whereas the thyroid dose is mostly due to internal inhalation and ingestion, which is about five times the external dose. This shows that the majority of dose comes from iodine whose thyroid dose coefficient is about 20 times greater than its effective dose coefficient.

These figures also show that soil ingestion contributed very little and that the dose from air inhalation was about double the water ingestion dose for both whole body effective and thyroid doses.

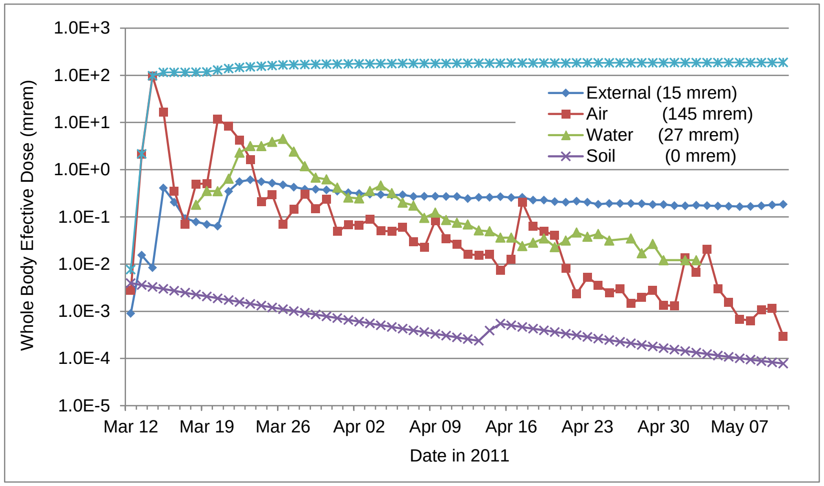


**Figure 50. Daily whole body effective dose for humanitarian relief at Yokota AB (D-8)**

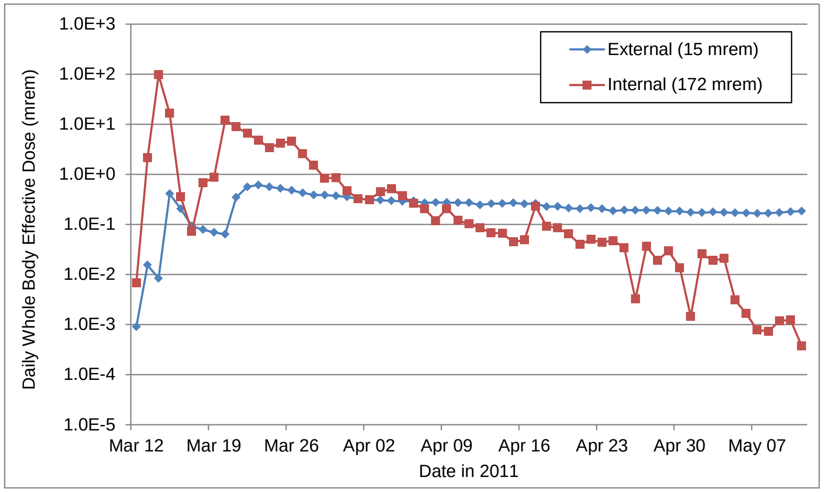


**Figure 51. Daily external and internal whole body effective dose for humanitarian relief at Yokota AB (D-8)**

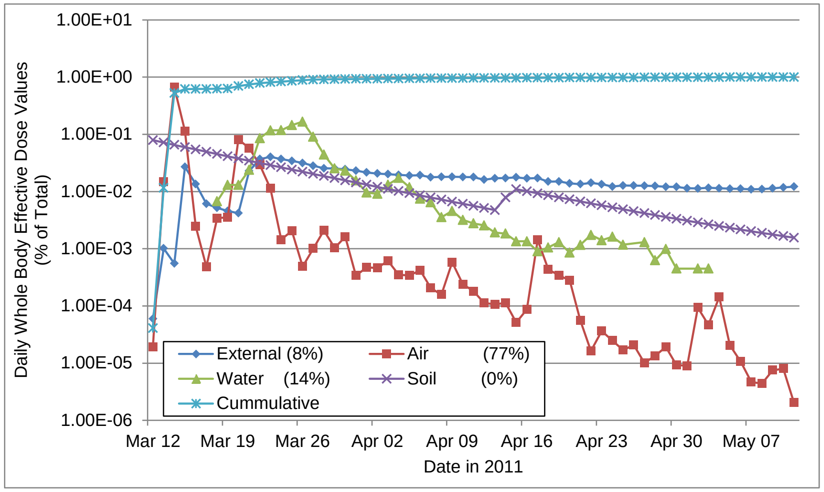


**Figure 52. Percent daily whole body effective dose for humanitarian relief at Yokota AB (D-8)**

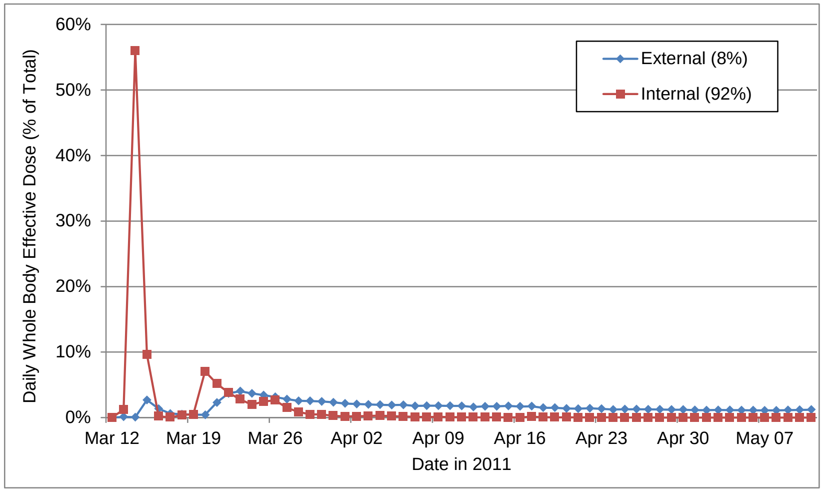


**Figure 53. Percent daily external / internal whole body effective dose for humanitarian relief at Yokota AB (D-8)**

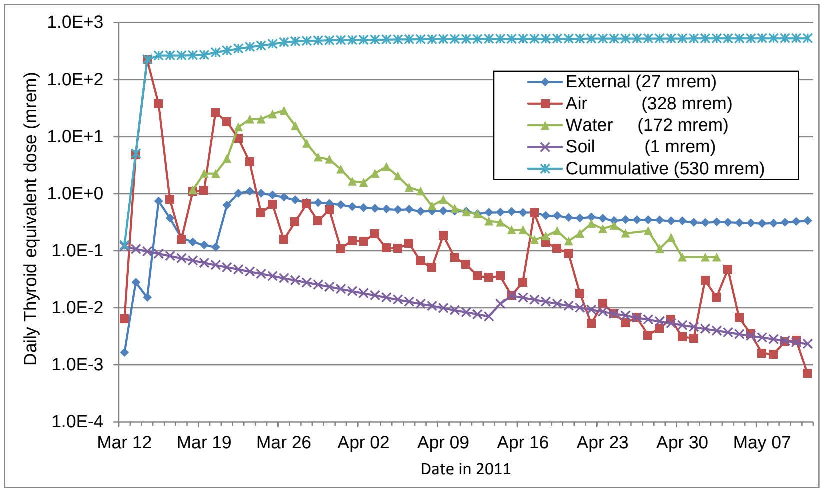


**Figure 54. Daily thyroid dose for humanitarian relief at Yokota AB (D-8)**

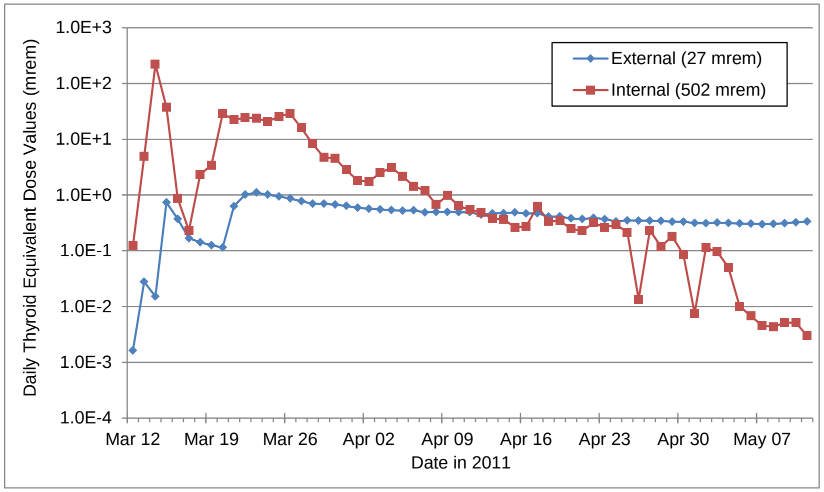


**Figure 55. Daily external / internal thyroid dose for humanitarian relief at Yokota AB (D-8)**

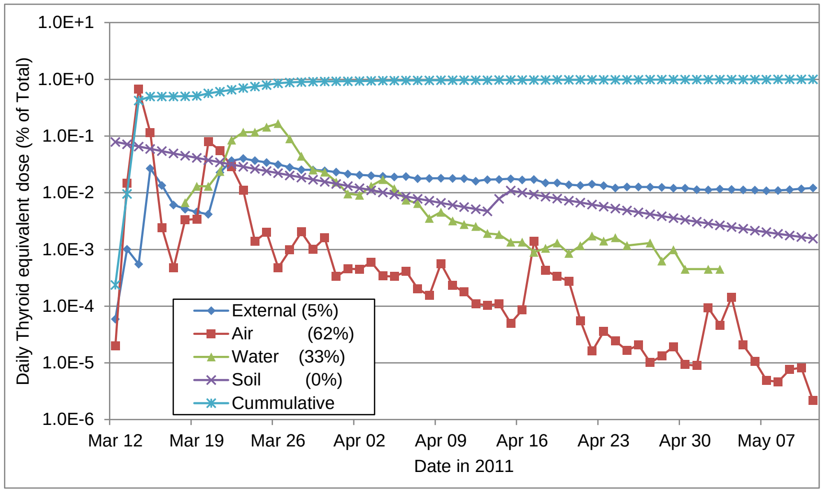


**Figure 56. Percent daily thyroid dose for humanitarian relief at Yokota AB (D-8)**

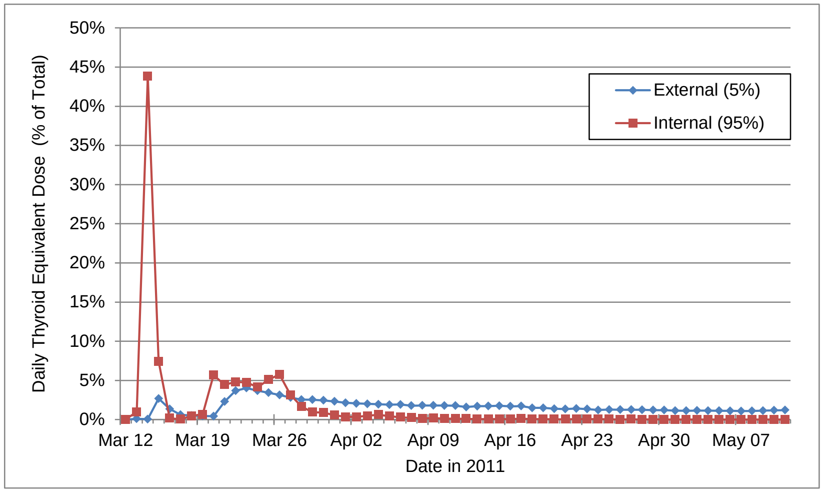


**Figure 57. Percent daily external and internal thyroid dose for humanitarian relief at Yokota AB (D-8)**

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# Section 6.

# Results and Discussion

## 6.1 Dose Results

The whole body effective and thyroid doses for children, under maximum exposure conditions at eight DARWG locations where they might have been present, are shown in Table 33 and Table 34. For adults performing humanitarian relief work, Table 35 and Table 36 list whole body effective and thyroid doses under maximum exposure conditions.

Although children have lower inhalation and ingestion rates than adults, their doses are higher than for adults under similar exposure conditions. The largest difference in doses occurs for the group aged greater than one to two years of age. These differences are reasonable because when compared to adults, children are more sensitive to ionizing radiation, their thyroid masses are smaller, and they retain radioactive materials for less time. Children's increased sensitivity is accounted for in the DCs used to calculate their doses. Children's thyroids absorb the same amount of energy as adult thyroids from the radioactive materials in them but since they are smaller the dose is greater. Although their thyroids are smaller and can receive a higher dose from an equal amount of radioactive material, their shorter retention times act to reduce the overall exposure time to radiation. The net result of the three competing factors of sensitivity to radiation, smaller thyroid mass, and reduced retention time is that whole body effective doses and thyroid doses are greater than for adults. For example, for Hyakuri AB (D-6) the children's maximum whole body effective and thyroid doses are 0.16 and 2.7 rem (1.6 and 27 mSv), whereas the highest adult values are 0.075 and 1.0 rem (0.75 and 10 mSv). Thus, the children's maximum whole body effective doses and thyroid doses are factors of 2.1 and 2.7 greater than the corresponding adult doses.

**Table 33. Whole body effective doses for children under maximum exposure conditions**

| DARWG Location (No.) | Dose for Age Group*,† | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 to 1 y | | >1 y to 2 y | | >2 y to 7 y | | >7 y to 12 y | | >12 y to 17 y | |
| | rem | mSv | rem | mSv | rem | mSv | rem | mSv | rem | mSv |
| Misawa AB (D-1) | 0.007 | 0.07 | 0.007 | 0.07 | 0.006 | 0.06 | 0.006 | 0.06 | 0.006 | 0.06 |
| Hyakuri AB (D-6) | 0.14 | 1.4 | 0.16 | 1.6 | 0.10 | 1.0 | 0.074 | 0.74 | 0.071 | 0.71 |
| Yokota AB (D-8)‡ | 0.088 | 0.88 | 0.099 | 0.99 | 0.071 | 0.71 | 0.055 | 0.55 | 0.053 | 0.53 |
| Akasaka Press Center (D-9)‡ | 0.079 | 0.79 | 0.090 | 0.9 | 0.061 | 0.61 | 0.046 | 0.46 | 0.044 | 0.44 |
| Atsugi NAF (D-10)‡ | 0.069 | 0.69 | 0.082 | 0.82 | 0.056 | 0.56 | 0.041 | 0.41 | 0.039 | 0.39 |
| Yokosuka NB (D-11)‡ | 0.063 | 0.63 | 0.077 | 0.77 | 0.051 | 0.51 | 0.036 | 0.36 | 0.033 | 0.33 |
| Camp Fuji (D-12) | 0.028 | 0.28 | 0.035 | 0.35 | 0.024 | 0.24 | 0.017 | 0.17 | 0.015 | 0.15 |
| Iwakuni MCAS (D-13) | 0.004 | 0.04 | 0.005 | 0.05 | 0.003 | 0.03 | 0.002 | 0.02 | 0.002 | 0.02 |
| Sasebo NB (D-14) | 0.005 | 0.05 | 0.007 | 0.07 | 0.004 | 0.04 | 0.003 | 0.03 | 0.003 | 0.03 |

*Doses were calculated based on conservative assumptions resulting in PEP doses that were greater than the 95th percentile values from the probabilistic dose analysis (Chehata et al., 2012).

†These PEP doses were calculated assuming no time indoors and highest physical activity levels.

‡Dose contributions from air inhalation at these sites were calculated using Yokota AB air concentration data.

**Table 34. Thyroid doses for children under maximum exposure conditions**

| DARWG Location (No.) | Dose for Age Group*,† | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 0 to 1 y | | >1 y to 2 y | | >2 y to 7 y | | >7 y to 12 y | | >12 y to 17 y | |
| | rem | mSv | rem | mSv | rem | mSv | rem | mSv | rem | mSv |
| Misawa AB (D-1) | 0.014 | 0.14 | 0.015 | 0.15 | 0.011 | 0.11 | 0.009 | 0.09 | 0.008 | 0.08 |
| Hyakuri AB (D-6) | 2.3 | 23 | 2.7 | 27 | 1.7 | 17 | 1.0 | 10 | 0.96 | 9.6 |
| Yokota AB (D-8)‡ | 1.2 | 12 | 1.4 | 14 | 0.88 | 8.8 | 0.54 | 5.4 | 0.51 | 5.1 |
| Akasaka Press Center (D-9)‡ | 1.2 | 12 | 1.4 | 14 | 0.86 | 8.6 | 0.53 | 5.3 | 0.50 | 5 |
| Atsugi NAF (D-10)‡ | 0.99 | 9.9 | 1.2 | 12 | 0.77 | 7.7 | 0.47 | 4.7 | 0.41 | 4.1 |
| Yokosuka NB (D-11)‡ | 0.99 | 9.9 | 1.2 | 12 | 0.77 | 7.7 | 0.46 | 4.6 | 0.41 | 4.1 |
| Camp Fuji (D-12) | 0.46 | 4.6 | 0.60 | 6 | 0.36 | 3.6 | 0.22 | 2.2 | 0.19 | 1.9 |
| Iwakuni MCAS (D-13) | 0.067 | 0.67 | 0.087 | 0.87 | 0.053 | 0.53 | 0.032 | 0.32 | 0.028 | 0.28 |
| Sasebo NB (D-14) | 0.085 | 0.85 | 0.11 | 1.1 | 0.067 | 0.67 | 0.042 | 0.42 | 0.035 | 0.35 |

*Doses were calculated based on conservative assumptions resulting in PEP doses that were greater than the 95th percentile values from the probabilistic dose analysis (Chehata et al., 2012).

†These PEP doses were calculated assuming no time indoors and highest physical activity levels.

‡Dose contributions from air inhalation at these sites were calculated using Yokota AB air concentration data.

**Table 35. Whole body effective doses for adults (humanitarian relief) under maximum exposure conditions**

| DARWG Location (No.) | External Radiation*,† | | Air Inhalation*,† | | Water Ingestion*,† | | Soil Ingestion*,† | | Total*,† | |
|---|---|---|---|---|---|---|---|---|---|---|
| | rem | mSv | rem | mSv | rem | mSv | rem | mSv | rem | mSv |
| Misawa AB (D-1) | 0.006 | 0.06 | <0.001 | <0.01 | <0.001 | <0.01 | <0.001 | <0.01 | 0.006 | 0.06 |
| Sendai Airport (D-2) | 0.039 | 0.39 | 0.039 | 0.39 | 0.040 | 0.4 | <0.001 | <0.01 | 0.12 | 1.2 |
| City of Ishinomaki (D-3) | 0.029 | 0.29 | 0.021 | 0.21 | 0.030 | 0.3 | <0.001 | <0.01 | 0.079 | 0.79 |
| City of Yamagata (D-4) | 0.015 | 0.15 | 0.021 | 0.21 | <0.001 | <0.01 | <0.001 | <0.01 | 0.036 | 0.36 |
| Hyakuri AB (D-6) | 0.023 | 0.23 | 0.034 | 0.34 | 0.017 | 0.17 | <0.001 | <0.01 | 0.075 | 0.75 |
| City of Oyama (D-7) | 0.025 | 0.25 | 0.037 | 0.37 | 0.026 | 0.26 | <0.001 | <0.01 | 0.087 | 0.87 |
| Yokota AB (D-8)‡ | 0.027 | 0.27 | 0.018 | 0.18 | 0.010 | 0.1 | <0.001 | <0.01 | 0.055 | 0.55 |
| Akasaka Press Center (D-9)‡ | 0.018 | 0.18 | 0.018 | 0.18 | 0.010 | 0.1 | <0.001 | <0.01 | 0.046 | 0.46 |
| Atsugi NAF (D-10)‡ | 0.018 | 0.18 | 0.018 | 0.18 | 0.003 | 0.03 | <0.001 | <0.01 | 0.039 | 0.39 |
| Yokosuka NB (D-11)‡ | 0.012 | 0.12 | 0.018 | 0.18 | 0.003 | 0.03 | <0.001 | <0.01 | 0.033 | 0.33 |
| Camp Fuji (D-12) | 0.006 | 0.06 | 0.009 | 0.09 | <0.001 | <0.01 | <0.001 | <0.01 | 0.015 | 0.15 |
| Iwakuni MCAS (D-13) | 0.001 | 0.01 | 0.001 | 0.01 | <0.001 | <0.01 | <0.001 | <0.01 | 0.002 | 0.02 |
| Sasebo NB (D-14) | 0.001 | 0.01 | 0.002 | 0.02 | <0.001 | <0.01 | <0.001 | <0.01 | 0.003 | 0.03 |

*Doses were calculated based on conservative assumptions resulting in PEP doses that were greater than the 95$^{th}$ percentile values from the probabilistic dose analysis (Chehata et al., 2012).

†These PEP doses were calculated assuming no time indoors and highest physical activity levels.

‡Dose contributions from air inhalation at these sites were calculated using Yokota AB air concentration data.

**Table 36. Thyroid doses for adults (humanitarian relief) under maximum exposure conditions**

| DARWG Location (No.) | External Radiation*,† | | Air Inhalation*,† | | Water Ingestion*,† | | Soil Ingestion*,† | | Total*,† | |
|---|---|---|---|---|---|---|---|---|---|---|
| | rem | mSv | rem | mSv | rem | mSv | rem | mSv | rem | mSv |
| Misawa AB (D-1) | 0.006 | 0.06 | <0.001 | <0.01 | <0.001 | <0.01 | 0.001 | 0.01 | 0.007 | 0.07 |
| Sendai Airport (D-2) | 0.039 | 0.39 | 0.59 | 5.9 | 0.59 | 5.9 | <0.001 | <0.01 | 1.2 | 12 |
| City of Ishinomaki (D-3) | 0.029 | 0.29 | 0.19 | 1.9 | 0.28 | 2.8 | 0.002 | 0.02 | 0.50 | 5 |
| City of Yamagata (D-4) | 0.015 | 0.15 | 0.43 | 4.3 | <0.001 | <0.01 | 0.002 | 0.02 | 0.45 | 4.5 |
| Hyakuri AB (D-6) | 0.023 | 0.23 | 0.68 | 6.8 | 0.30 | 3 | 0.004 | 0.04 | 1.0 | 10 |
| City of Oyama (D-7) | 0.025 | 0.25 | 0.73 | 7.3 | 0.38 | 3.8 | 0.004 | 0.04 | 1.1 | 11 |
| Yokota AB (D-8)‡ | 0.027 | 0.27 | 0.33 | 3.3 | 0.17 | 1.7 | 0.001 | 0.01 | 0.53 | 5.3 |
| Akasaka Press Center (D-9)‡ | 0.018 | 0.18 | 0.33 | 3.3 | 0.17 | 1.7 | 0.001 | 0.01 | 0.52 | 5.2 |
| Atsugi NAF (D-10)‡ | 0.018 | 0.18 | 0.33 | 3.3 | 0.061 | 0.61 | 0.001 | 0.01 | 0.41 | 4.1 |
| Yokosuka NB (D-11)‡ | 0.012 | 0.12 | 0.33 | 3.3 | 0.061 | 0.61 | 0.001 | 0.01 | 0.40 | 4 |
| Camp Fuji (D-12) | 0.006 | 0.06 | 0.18 | 1.8 | <0.001 | <0.01 | 0.001 | <0.01 | 0.18 | 1.8 |
| Iwakuni MCAS (D-13) | 0.001 | 0.01 | 0.026 | 0.26 | <0.001 | <0.01 | <0.001 | <0.01 | 0.027 | 0.27 |
| Sasebo NB (D-14) | 0.001 | 0.01 | 0.033 | 0.33 | <0.001 | <0.01 | <0.001 | <0.01 | 0.034 | 0.34 |

*Doses were calculated based on conservative assumptions resulting in PEP doses that were greater than the 95th percentile values from the probabilistic dose analysis (Chehata et al., 2012).
†These PEP doses were calculated assuming no time indoors and highest physical activity levels.
‡Dose contributions from air inhalation at these sites were calculated using Yokota AB air concentration data.

Doses shown in Table 33 through Table 36 are associated with the highest physical activity level and least amount of time indoors. Doses calculated for the remaining physical activity levels and times spent indoors as discussed in Section 3.4.2 are summarized for children in Table 37 and Table 38 and for adults and humanitarian relief individuals in Table 39 and Table 40.

**Table 37. Range of whole body effective doses (rem) to children at nine DARWG locations**

| DARWG Location (No.) | Age Group | | | | |
|---|---|---|---|---|---|
| | 0 to 1 y | >1 y to 2 y | >2 y to 7 y | >7 y to 12 y | >12 y to 17 y |
| Misawa AB (D-1) | 0.003–0.007 | 0.003–0.007 | 0.003–0.006 | 0.003–0.006 | 0.003–0.006 |
| Hyakuri AB (D-6) | 0.049–0.14 | 0.054–0.16 | 0.050–0.10 | 0.035–0.074 | 0.036–0.071 |
| Yokota AB (D-8) | 0.034–0.088 | 0.034–0.099 | 0.035–0.071 | 0.027–0.055 | 0.027–0.053 |
| Akasaka Press Center (D-9) | 0.029–0.079 | 0.029–0.090 | 0.030–0.061 | 0.022–0.046 | 0.022–0.044 |
| Atsugi NAF (D-10) | 0.026–0.069 | 0.028–0.082 | 0.028–0.056 | 0.021–0.041 | 0.021–0.039 |
| Yokosuka NB (D-11) | 0.023–0.063 | 0.025–0.077 | 0.025–0.051 | 0.018–0.036 | 0.018–0.033 |
| Camp Fuji (D-12) | 0.011–0.028 | 0.012–0.035 | 0.012–0.024 | 0.009–0.017 | 0.009–0.015 |
| Iwakuni MCAS (D-13) | 0.002–0.004 | 0.002–0.005 | 0.002–0.003 | 0.001–0.002 | 0.001–0.002 |
| Sasebo NB (D-14) | 0.002–0.005 | 0.002–0.007 | 0.002–0.004 | 0.002–0.003 | 0.002–0.003 |

Note: dose in millisievert (mSv) is 10 times the table entry

**Table 38. Range of thyroid doses (rem) to children at nine DARWG locations**

| DARWG Location (No.) | Age Group | | | | |
|---|---|---|---|---|---|
| | 0 to 1 y | >1 y to 2 y | >2 y to 7 y | >7 y to 12 y | >12 y to 17 y |
| Misawa AB (D-1) | 0.003–0.014 | 0.004–0.015 | 0.004–0.011 | 0.004–0.009 | 0.004–0.008 |
| Hyakuri AB (D-6) | 0.77–2.3 | 0.77–2.7 | 0.76–1.7 | 0.46 –1.0 | 0.47–0.96 |
| Yokota AB (D-8) | 0.41–1.2 | 0.4 –1.4 | 0.41 –0.88 | 0.24–0.54 | 0.25–0.51 |
| Akasaka Press Center (D-9) | 0.40–1.2 | 0.4–1.4 | 0.40–0.86 | 0.24–0.53 | 0.24–0.50 |
| Atsugi NAF (D-10) | 0.34–0.99 | 0.37–1.2 | 0.38–0.77 | 0.22–0.47 | 0.23–0.41 |
| Yokosuka NB (D-11) | 0.34–0.99 | 0.37–1.2 | 0.37–0.77 | 0.22–0.46 | 0.23–0.41 |
| Camp Fuji (D-12) | 0.15–0.46 | 0.18–0.60 | 0.18–0.36 | 0.11–0.22 | 0.11–0.189 |
| Iwakuni MCAS (D-13) | 0.023–0.067 | 0.026–0.087 | 0.026 –0.053 | 0.016–0.033 | 0.016–0.028 |
| Sasebo NB (D-14) | 0.029–0.085 | 0.034–0.11 | 0.033–0.067 | 0.02 –0.042 | 0.021–0.035 |

Note: dose in millisievert (mSv) is 10 times the table entry

**Table 39. Range of whole body effective doses (rem) to adults and humanitarian relief individuals at 13 DARWG locations**

| DARWG Location (No.) | Age Group | |
|---|---|---|
| | Adult | Humanitarian Relief |
| Misawa AB (D-1) | 0.003–0.006 | 0.006 |
| Sendai Airport (D-2) | 0.043–0.10 | 0.12 |
| City of Ishinomaki (D-3) | 0.028–0.068 | 0.079 |
| City of Yamagata (D-4) | 0.017–0.035 | 0.036 |
| Hyakuri AB (D-6) | 0.030–0.067 | 0.075 |
| City of Oyama (D-7) | 0.033–0.076 | 0.087 |
| Yokota AB (D-8) | 0.024–0.051 | 0.055 |
| Akasaka Press Center (D-9) | 0.019–0.042 | 0.046 |
| Atsugi NAF (D-10) | 0.018–0.037 | 0.039 |
| Yokosuka NB (D-11) | 0.015–0.031 | 0.033 |
| Camp Fuji (D-12) | 0.007–0.014 | 0.015 |
| Iwakuni MCAS (D-13) | 0.001–0.002 | 0.002 |
| Sasebo NB (D-14) | 0.001–0.003 | 0.003 |

Note: dose in millisievert (mSv) is 10 times the table entry

**Table 40. Range of thyroid doses (rem) to adults and humanitarian relief individuals at 13 DARWG locations**

| DARWG Location (No.) | Age Group | |
|---|---|---|
| | Adult | Humanitarian Relief |
| Misawa AB (D-1) | 0.003–0.007 | 0.007 |
| Sendai Airport (D-2) | 0.38–0.98 | 1.2 |
| City of Ishinomaki (D-3) | 0.14–0.4 | 0.5 |
| City of Yamagata (D-4) | 0.19–0.42 | 0.45 |
| Hyakuri AB (D-6) | 0.35–0.86 | 1.0 |
| City of Oyama (D-7) | 0.38–0.97 | 1.1 |
| Yokota AB (D-8) | 0.19–0.45 | 0.53 |
| Akasaka Press Center (D-9) | 0.18–0.44 | 0.52 |
| Atsugi NAF (D-10) | 0.16–0.37 | 0.41 |
| Yokosuka NB (D-11) | 0.16–0.36 | 0.4 |
| Camp Fuji (D-12) | 0.078–0.17 | 0.18 |
| Iwakuni MCAS (D-13) | 0.011–0.025 | 0.027 |
| Sasebo NB (D-14) | 0.015–0.032 | 0.034 |

Note: dose in millisievert (mSv) is 10 times the table entry

## 6.2 Comparisons with Dosimetric Measurements

### 6.2.1. Personnel Dosimetry

Personnel dosimeters were issued to individuals who were determined to have a potential for exposure to external radiation in performing their duties, such as assistance in humanitarian relief, entrance into the warm or hot zones, or as a routine requirement of their duties (occupations). The latter groups included nuclear trained individuals and medical individuals working with radiation sources. As discussed Appendix D-2, a few less than 3,200 personnel dosimeters had reported doses. The majority of those dose results (59.2 percent) were reported as zero rem, and almost all (99.6 percent) were reported as 0.025 rem (0.25 mSv) or less. These results compare favorably with the range of doses for the external component for adults reported in Table 35. Additional details of the personnel dosimetry process and results are in Appendix D-2.

### 6.2.2. Internal Monitoring

Almost 8,400 individuals were evaluated using internal monitoring (IM) for radionuclides deposited in their bodies. Individuals were selected for IM based on their potential for intake of radioactive materials during the response efforts. The evaluations were conducted in two phases, which scanned individuals with potential for exposure during Phase 1, and individuals who volunteered for scanning for various reasons, but mostly from concerns for their well-being. The total number evaluated was 8,380 with 8,225 in Phase I and 155 in Phase 2. Approximately 2 percent (183) of those monitored were found to exceed the IM instruments minimum detectable amount, and the highest committed effective dose of 0.025 rem (0.25 mSv) from internally-deposited radioactive materials. Details of the IM methods, procedures for selecting individuals for IM, and results are discussed in Appendix D-3.

## 6.3 Comparisons with other Radiological Events

The International Nuclear and Radiological Event Scale (INES) provides a standard for comparing nuclear and radiological events (IAEA, 2008). To date only two events have been rated as 7 - Major Accident; the Chernobyl event in 1986 and the FDNPS event in 2011. The Three Mile Island event near Harrisburg, Pennsylvania that occurred in 1979 was rated as 5 - Accident with Wider Consequences. The INES scale (See Figure 58) is intended to be logarithmic; each increasing level represents an event approximately ten times more severe than the previous level

Although Chernobyl and FDNPS both received an INES rating of seven, they differed in mortality outcomes. The Chernobyl accident caused the deaths of 30 power plant employees and firemen within a few days or weeks, including 28 deaths that were due to radiation exposure, and several thousand projected radiogenic deaths over the lifetime of the exposed population (WHO, 2006). Although some FDNPS workers were killed due to the tsunami, no deaths occurred due to acute radiation exposure, and lifetime radiogenic death projections are projected to be negligible (Harmon, 2012).

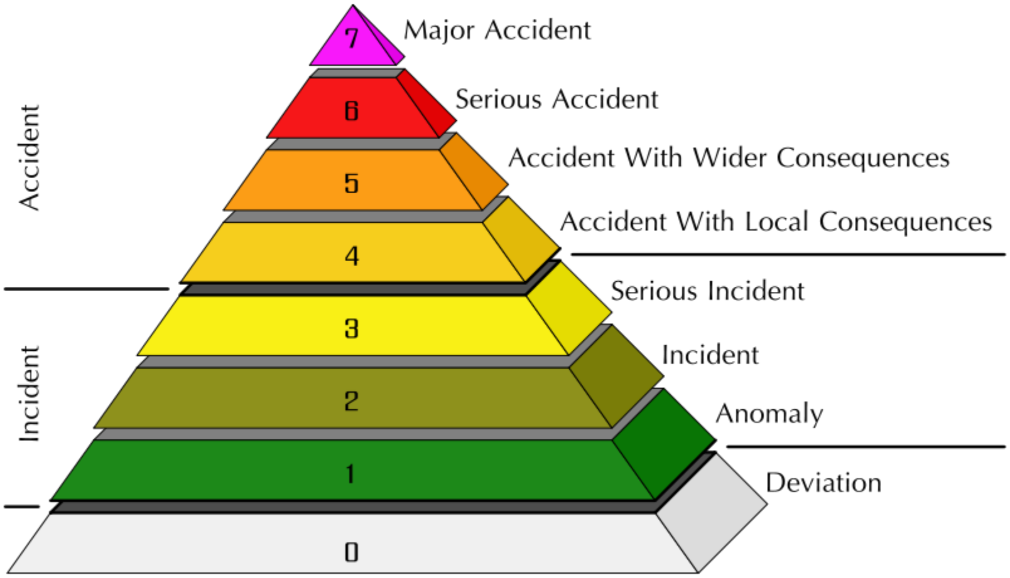


**Figure 58. International nuclear and radiological event scale**

Another useful comparison is notable environmental releases of I-131. Table 41 indicates that the FDNPS I-131 release was approximately one tenth of the Chernobyl release. Two significant differences between these two releases are that the activity of FDNPS release was at least ten times less than the Chernobyl release, and most of the FDNPS release blew out to sea, away from population centers. Even larger releases of radioiodines occurred during the 1950s in the western United States during nuclear weapons testing.

**Table 41. Notable environmental releases of I-131**

| Source | Event or Purpose | Period of Release | Activity (PBq)* | Reference |
|---|---|---|---|---|
| Three Mile Island | Nuclear Reactor Accident | Mar–Apr 1979 | 0.00074 | Kemeny, 1979 |
| Hanford, Washington | Plutonium Production | 1944–1956 | 27 | Napier, 2002 |
| FDNPS | Nuclear Reactor Accident | Mar–May 2011 | 150 | GOJ, 2011a |
| Chernobyl, Ukraine | Nuclear Reactor Accident | Apr–May 1986 | 1,800 | Apostoaei, 2004 |
| Nevada Test Site | Nuclear Weapons Testing | 1952–1957 | 5,600 | Apostoaei, 2004 |
| Worldwide Fallout | Nuclear Weapons Testing | 1952–1962 | 675,000 | Apostoaei, 2004; Beck, 2002 |

*1 PBq equals $1 \times 10^{15}$ Bq or ~27,000 curies
Table adopted from NCRP (2008); and GOJ (2011a) entry inserted.

## 6.4 Operation Tomodachi Doses in Perspective

### 6.4.1. Usage of Effective Dose

"The main and primary use of effective dose is to provide a means of demonstrating compliance with dose limits." (ICRP, 2007a) The effective dose is intended to limit adverse health effects such as cancer and inherited disorders and is intended to apply to age and sex averaged populations. Although effective dose can be used for initial studies and hypothesis generation, it is not the correct quantity for epidemiological studies of radiation risk (ICRP, 2007a). Because of these and other limitations, it is not appropriate to "calculate the hypothetical number of cases of cancer or heritable disease that might be associated with very small radiation doses received by large numbers of people over very long times [collective effective dose]" (ICRP, 2007a).

ICRP (2007a) suggests that "In retrospective assessments of doses to specified individuals that may substantially exceed dose limits, effective dose can provide a first approximate measure of the overall detriment" (ICRP, 2007a). In this sense, effective dose can provide a broad indication of potential risks within a given population exposed to radiation. However, greater care must be exercised when attempting to determine risks to specific individuals.

### 6.4.2. Comparison with the World Health Organization 2012 Report

The World Health Organization published a report entitled *Preliminary Dose Estimation – from the nuclear accident after the 2011 Great East Japan Earthquake and Tsunami*" (WHO, 2012). The WHO dose report used data collected and made publicly available by the Government of Japan (GOJ) through mid-September 2011. The WHO dose report includes exposures during one year following the accident. The WHO dose estimates were based on measurements of radioactivity in the air, soil, potable water and food supplies resulting from the accident. The dose estimates are provided in order-of-magnitude dose bands, with decreased band width at the higher levels of estimated doses. The presentation of doses to greater levels of numerical accuracy was considered by the panel to be inappropriate for the WHO report given the unquantified uncertainties of their assessment and its preliminary nature (WHO, 2012).

External doses were calculated based on ground deposition radiation measurements for the ground shine component, while the cloud shine component was based on atmospheric transport modeling. For the inhalation doses, the WHO assessment used atmospheric transport modeling based on Japanese source term estimates and surface activity of ground-deposited contamination to estimate air concentrations.

The WHO report includes dose results for the prefectures nearest the Fukushima prefecture and the areas in the rest of Japan. These areas are considered relevant to this report. Table 42 proves a comparison of the DOD and WHO radiation doses.

**Table 42. Summary comparison of DOD and WHO doses**

| Group | Effective Dose (rem [mSv]) | Thyroid Dose (rem [mSv]) |
|---|---|---|
| Children (<17 y) | 0.002 to 0.16 [0.02 to 1.6] | 0.008 to 2.7 [0.08 to 27] |
| Adults (≥17 y) | 0.002 to 0.12 [0.02 to 1.2] | 0.007 to 1.2 [0.07 to 12] |

### 6.4.3. Ubiquitous Background Radiation

Everyone is exposed to background radiation from the environment. Because this radiation is everywhere it is called ubiquitous background radiation. To place these OT doses in perspective, it is useful to compare doses received by the DOD-affiliated population with ubiquitous background radiation. Radiation exposure from medical procedures; consumer products; occupational activities; and industrial, security, medical, educational, and research sources of radiation are not included in the definition of ubiquitous background radiation (NCRP, 2009c).

#### *6.4.3.1 Whole Body Effective Dose Comparisons*

The mean annual effective dose to the U.S population from ubiquitous background radiation is about 0.310 rem (95 percent confidence interval of 0.094 to 1.21 rem [0.94 to 12.1 mSv]) (NCRP, 2009c). Radon-222 accounts for roughly 70 percent of the annual effective dose with a mean value of 0.212 rem (2.12 mSv) (95 percent confidence interval of 0.090 to 1.11 rem [0.9 to 11.1 mSv) (NCRP, 2009c).

Figure 59 is map of the main islands of Japan showing annual effective doses excluding the contribution from radon.[13] The mean value of the annual effective dose is about 0.099 rem (0.99 mSv) with a range of 0.081 to 0.119 rem (0.81 to 1.19 mSv). This mean value of 0.099 rem (0.99 mSv) is essentially equal to that in the United States (~0.098 rem; 0.98 mSv), but the range of Japanese values is much narrower. If the dose from radon is included then the annual effective dose from ubiquitous background radiation in Japan is about 0.15 rem[14] (1.5 mSv) compared with about 0.31 rem (3.1 mSv) for the United States.

[13] Taken from Radiation in Daily Life, www.eu.emb-japan.go.jp/pdfs%20and%20docs/radiationindaily%20life.pdf. (Accessed April 7, 2012.)
[14] See http://www.kankyo-hoshano.go.jp/04/04-1.html (Accessed August 24, 2012) and http://en.wikipedia.org/wiki/Background_radiation (Accessed August 24, 2012)

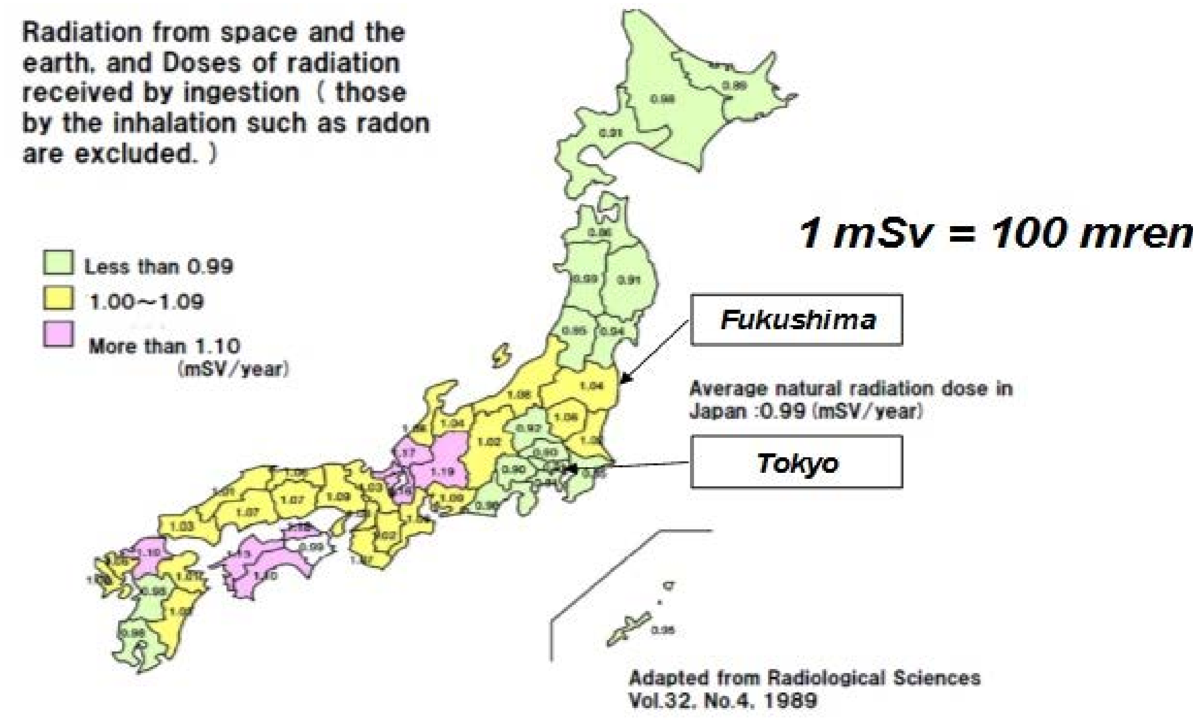


**Figure 59. Map of ubiquitous background annual effective dose in Japan (excluding Radon)**

The radiation doses calculated for the sixty-day period considered in this report are shown in Table 43. When compared to a lifetime exposure (70 y), the calculated effective doses are very small as seen in Table 43, with all effective doses from Operation Tomodachi contributing less than one percent to the lifetime effective dose.

**Table 43. Comparison of 60-day and lifetime (70 y) effective doses from Operation Tomodachi to doses from ubiquitous background in the United States and Japan**

| Exposure Period | Country | Dose (rem [mSv]) | Operation Tomodachi (60 d) (rem [mSv]) |
|---|---|---|---|
| 60 days | United States | ~0.051 [0.51][*,†] | 0.008 to 2.7 [0.08 to 27] (Children)<br>0.007 to 1.2 [0.07 to 12] (Adults) |
| | Japan | ~0.025 [0.25] | |
| Lifetime (70 y) | United States | ~22 [220][*,‡] | 0.002 to 0.16 [0.02 to 1.6] (Children)<br>0.002 to 0.12 [0.02 to 1.2] (Adults) |
| | Japan | ~10 [100] | |

[*]Including radon contributions
[†]Approximate 95$^{th}$ percentile range = 0.015–0.199 rem (0.15–1.99 mSv). Calculated by prorating the annual data presented in NCRP Report 160. (NCRP, 2009a).
[‡]Approximate 95$^{th}$ percentile range = 6.6–85 rem (66–850 mSv). Calculated by prorating the annual data presented in NCRP Report 160. (NCRP, 2009a).

### 6.4.3.2 Thyroid Dose

The thyroid is exposed to background radiation from both external and internal sources of radiation. The thyroid doses calculated for the sixty-day period considered in this report and the doses from ubiquitous background for 60 days of exposure and for a lifetime of 70 years are shown in Table 44. In the current context of a lifetime exposure (70 y), the calculated thyroid doses (children, 2.7 rem [27 mSv]) can contribute up to an additional 50 percent to the lifetime thyroid dose (5.4 rem [54 mSv]) as listed in Table 44.

Table 45 lists the arithmetic mean of specified sources of radiation exposure to the thyroid from ubiquitous background in the United States [adapted from NCRP (2009) data]. Both external and internal sources of radiation exposure are considered. Two major assumptions were made in creating Table 45:

- All external radiation exposure is uniform over the entire body, and
- Internal radiation sources listed deliver their radiation doses uniformly throughout the body (except as noted).

Under these assumptions the thyroid dose is approximately equal to the effective dose.

**Table 44. Comparisons of 60-day and lifetime (70 y) thyroid doses**

| **United States (rem [mSv])** | | **Operation Tomodachi (60 d) (rem [mSv])** |
|---|---|---|
| 60 day | ~0.013 [0.13]* | 0.008 to 2.7 [0.08 to 27] (Children) |
| Lifetime (70 y) | ~5.4 [54]† | 0.007 to 1.2 [0.07 to 12] (Adults) |

*Approximate 95th percentile range = 0.009–0.016 rem. Calculated by prorating the annual doses in Table 45.
†Approximate 95th percentile range = 4.0–6.8 rem. Calculated by prorating the annual data in Table 45.

**Table 45. Contributions to thyroid dose from ubiquitous background in the U.S.**

| Source and Dose Type | Equivalent or Effective Dose (mSv)* | Thyroid Dose (rem)* | Notes |
|---|---|---|---|
| U-Th Series in the Body† (Equivalent dose) | 0.069 | 0.0069 | Adults, Internal |
| Space‡ (Effective Dose) | 0.33 ± 0.08 | 0.033 ± 0.008 | Adult males<br>External dose assumed uniform to whole body; therefore effective dose ≈ equivalent dose. |
| Terrestrial‡ (Effective Dose) | 0.21 ± 0.06 | 0.021 ± 0.0066 | Adult males<br>External dose assumed uniform to whole body; therefore effective dose ≈ equivalent dose. |
| K-40‡ (Effective Dose) | 0.15 ± 0.02 | 0.015 ± 0.002 | Adult males<br>Internal dose assumed uniform to whole body; therefore effective dose ≈ equivalent dose. |
| C-14 and Rb-86‡ (Effective Dose) | 0.01 ± 0.001 | 0.001 ± 0.0001 | Adult males<br>Internal dose assumed uniform to whole body; therefore effective dose ≈ equivalent dose. |
| Total** = | | 0.077 ± 0.010†† | |
| 90 percent confidence interval (2.5 to 97.5 percent) | | 0.057 to 0.097 | Assume normally distributed values and neglects the uncertainty in U-Th series equivalent dose |

*Arithmetic Mean (± 1σ)

†Table 3.12 (NCRP, 2009), "average" value and no uncertainty given.

‡Table 3.14 (NCRP, 2009), The "annual effective doses to women and children are comparable, but [as explained in NCRP Report No. 160 (NCRP, 2009)] the data are too sparse to produce equally detailed summaries for women and children."

**The equivalent dose resulting from the inhalation of Rn-220 and Rn-222 is neglected because most of the equivalent dose is to the lung.

††This standard deviation likely underestimates the true standard deviation of the sum because the contribution from the U-Th series and the effects of combining normally and log-normally distributed variables are neglected.

### 6.4.4. Medical Procedures

#### *6.4.4.1 Effective Dose*

The whole body effective dose from diagnostic medical procedures varies quite widely depending on the particular procedure and area of body under examination. In general, the whole body effective dose from these procedures varies from about 0.001 rem (0.01 mSv) to more than 5 rem (50 mSv). Children’s doses from diagnostic nuclear medicine procedures were not explicitly considered for this report because dosages are prescribed according to body weight. In general, children’s whole body effective doses fall into the same range as adults. For example, according to the thyroid uptake procedure reviewed, the range of effective doses to a five-year old child is 0.084 to 0.4 rem (0.84 to 4.0 mSv). The effective doses are about the same as for adults because although the radiation dose per unit of radiopharmaceutical is greater in children than adults, a much smaller amount of a radiopharmaceutical is used for children.

#### *6.4.4.2 Thyroid Dose*

For conventional radiography and computed tomography procedures, the thyroid dose for adults can range from a small fraction of a rem (less than 0.001 rem [0.01 mSv]) to about 5 rem (50 mSv). Thyroid doses for nuclear medicine diagnostic procedures, at least for adults, are all greater than 1 rem (10 mSv) and reach over 100 rem (1000 mSv). Children's thyroid doses from diagnostic nuclear medicine procedures were not explicitly compared for this report because dosages are prescribed according to body weight. In general, children's thyroid doses are about the same for adults because the radiation dose per unit radiopharmaceutical is greater in children than in adults but a much smaller amount is used. For example, according to the thyroid uptake procedure reviewed the range of thyroid doses to a 5 year old child is 5.9 rem (59 mSv) to 70 rem (700 mSv).

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# Section 7.

## Conclusions

The radiation doses in this report are the result of an assessment of exposures to the radiological conditions in Japan during the sixty days between March 12 and May 11, 2011. For the population of interest, the OT-related radiation doses for representative adults and children were calculated based on high-sided intakes rates and environmental data collected by the DOD, DOE, and the GOJ at different locations throughout Japan. The assessment focused on the prefectures of Aomori, Kanagawa, Nagasaki, and Tokyo where most of the U.S. DOD-affiliated population was located, but also included individuals near Sendai in the Miyagi prefecture. Assessments were not performed for individuals in the Okinawa prefecture because dose rate monitoring data demonstrated no significant difference from pre-accident background rates.

Comparisons of the OT-related radiation doses with internal and external monitoring results indicate that the doses calculated in this report overestimate actual radiation doses among the POI. The results of internal monitoring cannot be directly compared with the results of this assessment mainly because detailed location and physical activity data were not available for monitored individuals at the time this report was written. However, the DARWG believes actual radiation doses to any individual in the POI personnel are less than the doses in this report.

For adults, performing humanitarian relief efforts, and children, the calculated effective doses for all locations fall into a range of about 0.01 to 0.2 rem (0.1 to 2 mSv), and the thyroid doses range from about 0.01 to 3 rem (0.1 to 30 mSv). Radiation doses tend to be higher in children than in adults exposed under the same conditions as expected. These radiation doses are low and would not require any intervention under U.S. radiological protection guidance. Any estimate of the probability of adverse health effects based on the ranges of radiation doses calculated in this report should be approached with caution. At effective doses less than about 5 to 10 rem (50 to 100 mSv), “risks of health effects are either too small to be observed or are nonexistent” (HPS, 2010).

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# Section 8.

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# Appendix A.

## Radiation Instrumentation

### A-1. Portable Radiation Survey Instruments

DOD and DOE individuals used several different types of portable survey instruments to measure external exposure or dose rates. The detectors included gas ionization detectors and scintillation detectors. The following subsections discuss the instruments used to perform surveys of air filters and soil samples and to measure contamination levels on surfaces.

#### A-1.1. AN/VDR-2, AN/PDR-77 Survey Meters

Most USA and Marine Corps external radiation exposure measurements used for external dose reconstruction were made using either an AN/VDR-2 or an AN/PDR-77 survey meter. The AN/VDR-2 is equipped with two detectors—a low range, energy-compensated Geiger-Mueller (G-M) detector capable of detecting beta particles and gamma ray photons, and a high range, energy-compensated G-M detector. The low range detector has a mica window for beta detection. The low range beta/gamma G-M detector has a range of 0.01 µGy $h^{-1}$ to 5 Gy $h^{-1}$. The high range gamma detector has a range from 0.03 Gy to 100 Gy $h^{-1}$ (USA, 1988). The AN/VDR-2's low-range, energy-compensated G-M detector has a dose rate accuracy of 20 percent at 10 Gy $h^{-1}$ and 10 percent at 5 µGy $h^{-1}$, and an energy response that is considered flat for photons with energies above 200 keV. The instrument is capable of measuring doses with an error of 10 percent when exposed to Cs-137 and Co-60 (Oliver and Heimbach, 1998). A picture of the AN/VDR-2 is in Figure A-1 (DTRA, 2005).


**Figure A-1. AN/VDR-2 RADIAC meter**

### A-1.2. Canberra ADM-300 Survey Meter

Most USAF external radiation exposure rate measurements used for external dose reconstruction were made using a Canberra ADM-300 survey meter. The ADM-300 is equipped with two built-in gamma radiation, energy compensated G-M detectors. The low-range detector has a range of 0.01 μGy $h^{-1}$ to 0.05 Gy $h^{-1}$. The high-range G-M detector has a range of 0.05 to 100 Gy $h^{-1}$. The instrument has an accuracy of 10 percent for gamma energies from 80 keV to 3 MeV. (Armstrong et al., 1992) The instrument has a non-linearity of 5 percent (Southern Scientific, undated). The ADM-300 was also used with a Canberra BP-120 G-M detector and an AP-100 alpha detector. The BP-120 has a thin window with an effective window diameter of 4.45 cm. The BP-120 has an efficiency of 26 percent for Sr-90, 18 percent for Cs-137, 9 percent for Tc-99, and 2 percent for C-14. The AP-100 is a zinc-sulfide scintillation detector with a Mylar shield over the scintillator. The AP-100 alpha detector has a total window area of 123 $cm^2$. The AP-100 has an efficiency of 10 percent for Pu-239 (Rademacher, 2005). A picture of the ADM-300 is shown in Figure A-2 (DTRA, 2005).


**Figure A-2. Canberra ADM-300 survey meter**

### A-1.3. Navy Survey Meters

Most USN external radiation measurements were made using the IM-265/PDQ—also known as the Multi-Function RADIAC meter. There are several combinations of the IM-265/PDQ with various probes; each combination of the meter with a specific probe takes on a new AN-PDQ nomenclature. Table A-1 shows the names used for different IM-265/PDQ-probe combinations. The table also shows other USN equipment appropriate for performing external radiation contamination surveys on individuals. Some of this equipment could have been, and probably was used during OT.

The IM-265/PDQ meter is equipped with one internal G-M detector. However, the IM-265/PDQ can be equipped with an external Thermo Scientific HP-210 probe or SPA-3 probe (DOE, 1996). The internal, energy-compensated G-M detector detects photons with energy greater than 80 keV with an accuracy of 15 percent. The instrument has a range from 0.01 mGy $h^{-1}$ to 10 G $h^{-1}$ (DOD, 2005). The HP-210 probe is a G-M "pancake" detector with a thin mica window, a protective stainless steel screen, and a tungsten shield. The HP-210 probe is capable of detecting beta particles with energies as low as 40 keV. The HP-210 has a beta efficiency of 22 percent for Cs-137, 32 percent for Sr-90, and 15 percent for Tc-99 (Thermo Electron, 2007a). A picture of the AN/PDQ-1 with assorted probes is in Figure A-3.

**Table A-1. USN survey meters appropriate for performing external radiation contamination surveys of individuals**

| Configuration | Description | Remarks |
|---|---|---|
| AN/PDQ-1 | 1. Multi-Function RADIAC Control Unit (MFRCU) - IM-265/PDQ | Internal gamma probe – G-M tube<br>No beta capabilities |
| AN/PDQ-3 | 1. MFRCU - IM-265/PDQ<br>2. Probe with thick beta window DT-680/PDQ | Beta probe has a relatively thick window not appropriate for individual contamination. |
| AN/PDQ-4 | 1. MFRCU - IM-265/PDQ<br>2. DT-685/PDQ Interface between IM-265/PDQ and DT-304 Probe<br>3. Beta Probe with thin Mylar window - DT-304 | |
| AN/PDQ-5 | 1. MFRCU<br>2. Alpha Probe DT-681/PD | |
| AN/PDQ-7 | 1. Frisker Station IM-271/PDQ<br>2. Beta probe with thin Mylar window - DT-304 | |
| GR135HD Exploranium | Isotopic Identifier | |
| IM-231 | Detects and measures x-ray and gamma dose rates. No beta capabilities | |
| IM-249 | 1. Frisker Station IM-249 with Tc-99 Source<br>2. Beta Probe with thin Mylar window - DT-304 | AC or Battery Powered |
| IM-254 | 1. Frisker Station IM-254 with Tc-99 Source<br>2. Beta Probe with thin Mylar window - DT-304 | AC Powered |


**Figure A-3. AN/PDQ-3 consisting of IM-265/PDQ Multifunction RADIAC with probes and interface unit**

### A-1.4. Thermo Scientific RadEye PDR-ER Survey Meter

USA veterinary units in Japan used the Thermo Scientific RadEye PDR-ER to perform surveys of food and material. The detector is an NaI(Tl) detector with an energy range of 60 keV to 1.3 MeV and is capable of detecting from 0.01 μGy $h^{-1}$ to 0.1 Gy $h^{-1}$. The system has a dose linearity of 20 percent for Cs-137 (Thermo Scientific, 2008). A picture of the RadEye PRD-ER is in Figure A-4.

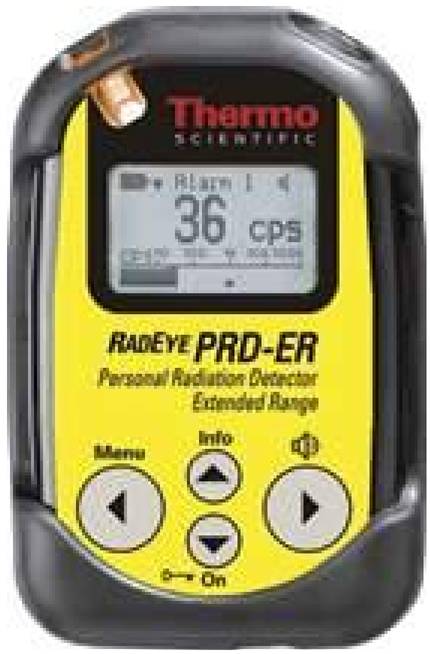


**Figure A-4. Thermo Scientific RadEye PRD-ER survey meter**

### A-1.5. Fluke 451P Survey Meter

AFRAT personnel used Fluke 451P survey meters to measure radiation exposure rates in the SENDAI area and other locations. The Fluke 451P's air ionization chamber has a 230-$cm^3$ detector volume filled to 6 atmospheres pressure, and is capable of detecting gamma radiation with energies above 25 keV. The instrument has a 200 mg $cm^{-2}$-thick plastic casing surrounding the ionization chamber. The Fluke 451P has a dose range 0.01 µGy $h^{-1}$ to 0.05 Gy $h^{-1}$. The instrument is accurate to 10 percent for readings between 10 percent and 100 percent of full scale in any range and has a precision of 5 percent. The detector has a response relative to Cs-137 of less than 1.0 for photon energies below 40 keV and 1.4 for photon energies of 100 keV (Fluke, 2005). A picture of the 451P is in Figure A-5.

**Figure A-5. Fluke 451P survey meter**

### A-1.6. Eberline ESP-2 Survey Meter

USA units used the Eberline Smart Portable 2 (ESP-2) survey meters with HP-260 probes to measure air filters and ground contamination. The ESP-2 is a data-logging, portable radiation survey instrument that can operate in either rate meter or scaler mode (Eberline Corporation, 1996). The HP-260 probe contains a pancake G-M tube detector with a thin mica window and a steel screen. The HP-260 probe can detect beta particles with energies greater than 40 keV. The HP-260 probe has an efficiency of 22 percent for Cs-137, 32 percent for Sr-90, and 15 percent for Tc-99 (Thermo Scientific, 2007b). A picture of the ESP-2 survey meter is in Figure A-6.


**Figure A-6. Eberline ESP-2 survey meter**

### A-1.7. Ludlum 2360 Survey Meter

AFRAT used Ludlum 2360 alpha/beta data-logger, survey meters to make ground contamination measurements. The Ludlum 2360 can operate in scaler, ratemeter, or data logger mode, and was used with the Ludlum 43-89 alpha/beta scintillator probe. The 43-89 probe contains both a zinc-sulfide scintillator for detecting alpha particles and a plastic scintillator for detecting beta particles, and has an active window area of 125 $cm^2$ (Ludlum Measurements Corporation, 2011a). The meter has an accuracy of 10 percent from the average reading. The 43-89 probe has an efficiency of 20 percent for Pu-239, 15 percent for Tc-99, and 20 percent for Sr-90 (Ludlum Measurements Corporation, 2010). A picture of the Ludlum 2360 survey meter is in Figure A-7.

**Figure A-7. Ludlum 2360 survey meter**

### A-1.8. Ludlum 2221 Survey Meter

AFRAT used Ludlum Model 2221 general purpose rate meter/scalers to make ground contamination measurements. The Ludlum 2221 is capable of functioning as a rate meter, a single channel analyzer, or a scaler (Ludlum Measurement Corporation, 2011b). The Ludlum Model 2221 was equipped with a Thermo Electron SPA-3 Scintillation probe. The SPA-3 probe is a scintillation detector with a 2″ x 2″ sodium-iodide detector housed in an aluminum case. The SPA-3 probe can detect photons within an energy range of 60 keV to 2 MeV. The SPA-3 probe typically over-responds to photons at 100 keV by a factor of 10 and under-responds to photons at 1 MeV by a factor of 0.5 relative to its response to Cs-137 (Johnson, 2009). A picture of the Ludlum 2221 survey meter is in Figure A-8.

**Figure A-8. Ludlum 2221 survey meter**

### A-1.9. Bicron Analyst Survey Meter

AFRAT used a Bicron Analyst with a pancake G-M detector to perform contamination surveys. The Bicron Analyst is a portable count rate meter that may be used with a variety of G-M, proportional or scintillation detectors for the detection of alpha, beta, x-ray or gamma, and neutron radiation. The instrument uses a single channel analyzer to provide three modes of operation, which allows energy discrimination and significant background reduction (Bircon/Harshaw, 1996). The pancake G-M probe is a thin-windowed probe that has an effective window size of 44.5 mm (Clarke, B. 2006). A picture of the Bicron Analyst is in Figure A-9.


**Figure A-9. Bicron Analyst survey meter**

## A-2. External Personnel Monitoring Instruments

External personnel monitoring was performed using three unique technologies: the USAF and USN electronic personal dosimeter (EPD), the USAF and USN thermoluminescent dosimeters (TLD), and the USA optically stimulated luminescent (OSL) dosimeter. Salient features of these personnel monitoring devices are described in the following subsections.

### A-2.1. Thermo Scientific MK2 Electronic Personal Dosimeter

USAF and USN units in Japan used, and issued to others, the Thermo Scientific MK2 EPD for monitoring of external radiation exposures while in Japan and for those U.S. service members who travelled to areas close to the FDNPS reactors. The MK2 EPD uses multiple diode detectors to measure personal exposures to photons with energies ranging from 15 keV to 10 MeV. The MK2 EPD has a dose range from 0 mrem to 1600 rem with a dose rate range of 0 mrem $h^{-1}$ to 400 rem $h^{-1}$. The MK2 has an accuracy of 50 percent at 17 keV, 20 percent at energies between 17 keV and 1.5 MeV, 30 percent at photon energies between 1.5 MeV and 6 MeV, and 40 percent at photon energies from 6 MeV to 10 MeV (Thermo Scientific, 2009). The dosimetry service that used the MK2 system and the deployable field laboratory to assess radiation exposures is accredited by the National Voluntary Laboratory Accreditation Program (NVLAP) under NVLAP code 100548-0 (NIST, 2011). A picture of the MK2 EPD is in Figure A-10.


**Figure A-10. Thermo MK2 electronic dosimeter**

### A-2.2. DT-702/PD Personal Dosimeter

Naval individuals and others were issued the DT-702/PD (US Navy, 2011). The DT-702/PD LiF TLD is designed to measure beta, gamma, x-ray, and neutron radiation. This personnel radiation dosimeter has four LiF TLD elements on a card and is used with a black card holder. The DT-702/PD TLD card consists of four LiF:Mg, Cu, P TL elements of different thicknesses and compositions mounted between two Teflon sheets on an aluminum substrate. The TLD card holder covers each TL element with a filter providing different radiation absorption thicknesses to allow evaluation of deep and shallow dose equivalent radiation. Elements 1, 2, and 3 are Li-7, which is sensitive to photon and beta radiation. Element 4 is Li-6, which is sensitive to photon, beta, and neutron radiation. The dosimeters were processed either at Yokosuka NB or at the Naval Dosimetry Center, Bethesda, MD.

The DT-702/PD is capable of detecting doses from 0.1 mrem to 2000 rem, with a linearity of 1 percent (Thermo Scientific, 2011). This dosimetry system is accredited under NVLAP code 100504-0 (NIST, 2011). Pictures of the dosimeter reader and DT-702/PD are in Figure A-11.

**Figure A-11. DT-702/PD dosimeter and reader**

### A-2.3. Panasonic Personal Dosimeter

USAF individuals and others were issued Panasonic TLDs (model UD-802AT). This passive dosimeter is used for whole body exposure monitoring. This four element TL dosimeter is sensitive to photon, beta and neutron radiation and is processed using a Panasonic UD-7900M Automatic TLD Reader. Dosimeter elements 1 & 2 are lithium borate and elements 3 & 4 are calcium sulfate. Lower limit of detection is 10 mrem. This dosimetry system is accredited under NVLAP code 100548-0 (NIST, 2011). A picture of the dosimeter is shown in Figure A-12.

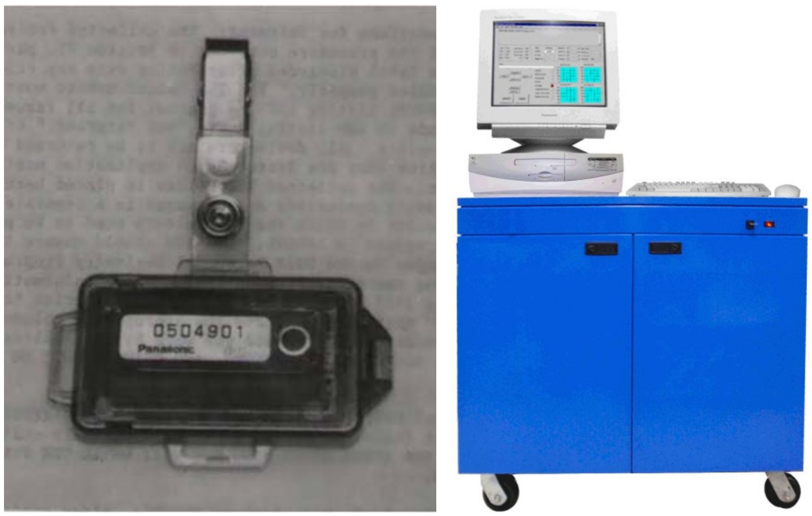


**Figure A-12. Panasonic dosimeter and reader**

### A-2.4. Landauer Personal Dosimeter

USA individuals and others were issued OSL personal dosimeters that use an aluminum oxide detector that is read out using a light emitting diode array to stimulate the aluminum oxide. The OSL system, manufactured by Landauer, Inc. is capable of measuring doses from 1 mrem to 1000 rem. The OSL dosimeter has a gamma energy range from 5 keV to 200 MeV and has a minimal reporting dose of 5 mrem. The OSL dosimeter is read out using an InLight Systems Reader (Landauer, 2008). The OSL system is accredited under NVLAP code 100504-0 (NIST, 2011). A picture of the OSL badge and reader are in Figure A-13.


**Figure A-13. Landauer dosimeter and reader**

## A-3. Internal Personnel Monitoring Instruments

Internal monitoring (IM) measurements were made to assess internally deposited radioactive material to include radioactive iodine deposited in the thyroid. Two types of systems were used. Screening measurements were made of the thyroid and lung using portable survey equipment. More definitive whole body counter measurements were made using dedicated whole body counters. The IM systems include those discussed in the following subsections.

### A-3.1. Eberline E-600 Survey Meter

Internal monitoring of the thyroid and lungs was performed using an Eberline E-600 multipurpose survey meter equipped with a SPA-3 scintillation detector. The E-600 is capable of operating in rate-meter, scalar, integration, peak trap, and background mode (Thermo Electron, 2004). The SPA-3 probe is a scintillation detector with a 2″ x 2″ sodium-iodide detector housed in an aluminum case. The SPA-3 probe can detect photons with an energy range of 60 keV to 2 MeV. The SPA-3 probe typically over-responds to photons at 100 keV by a factor of 10 and under-responds to photons at 1 MeV by a factor of 0.5 relative to its response to Cs-137 (Johnson, 2009). Pictures of an E-600 survey meter and a SPA-3 probe are in Figure A-14.

**Figure A-14. Eberline E-600 meter and SPA-3 detector**

### A-3.2. Canberra ACCUSCAN II

Internal whole-body monitoring was performed using a Canberra ACCUSCAN II scanning germanium whole-body counter. The ACCUSCAN II system is equipped with a 25 percent coaxial germanium detector and a shadow shield of four inches of steel supplemented with two inches of lead around the detector. The ACCUSCAN II is capable of detecting photons with energies between 100 keV and 1336 keV. The system comes with ABACOS software (Canberra, 2002a). A picture of the ACCUSCAN II is in Figure A-15.


**Figure A-15. Canberra ACCUSCAN II whole-body counter**

### A-3.3. Canberra Model 2250 FASTSCAN

Internal whole body monitoring was performed using a Canberra Model 2250 FASTSCAN high-throughput, whole-body counter. The FASTSCAN system is equipped with two large area (3 inch by 5 inch by 16 inch) sodium iodide detectors and two shadow shields of four inches of steel. The instrument is capable of detecting photons with energies between 300 keV and 1.8 MeV. The system has a lower limit of detection of 150 Bq with a person in the shield. The system comes with ABACOS software (Canberra, 2002b). A picture of the Canberra FASTSCAN is in Figure A-16.


**Figure A-16. Canberra FASTSCAN whole-body counter**

## A-4. Air Sampling Instruments

Air sampling was performed using low and high-volume air samplers and a variety of air filter types. The air sampling systems and filter types are discussed in the following subsections.

### A-4.1. Hi-Q Air Samplers

Two types of Hi-Q air samplers were used for air sampling—the Hi-Q C-900 series and the Hi-Q/Staples TFIA series samplers. AFRAT used the Hi-Q CF-995B battery-powered, air sampler. The CF-995B is capable of flow rates of 30 to 175 liters $min^{-1}$ (1.1 to 6.2 $ft^3$ $min^{-1}$) and can use both filter paper (cellulose or glass fiber) or filter cartridges (Hi-Q Environmental Products Company, Inc., 2010). The C-995B appears to have been used in conjunction with the Hi-Q FP2063-47 glass fiber filter to collect particulate samples. The FP2063-47 has an efficiency of 97 percent for 0.3 µm particles, has a thickness of 0.16 in, and is made of 100 percent borosilicate glass microfiber. Some collections used the Hi-Q TC-12 filter cartridge to sample airborne iodine and other gaseous radioactive materials. The TC-12 cartridge contains 5 percent triethylene di-amine (TEDA) impregnated charcoal with particle size 8 × 16 mesh and has dimensions of 2.25″ by 1″.

The Hi-Q TFIA sampler, which is similar to the Staplex TFIA sampler (see Figure A-19), is capable of a maximum flow rate of 40 $ft^3$ $min^{-1}$ or 25 $ft^3$ $min^{-1}$ when using the 4-inch filter holder. Pictures of the CF-995B air sampler and the TC-12 air sample cartridge are in Figure A-17.


**Figure A-17. Hi-Q CF-995B air sampler and TC-12 iodine sample cartridge**

### A-4.2. RADēCO Air Samplers

Two types of RADēCO samplers were used for air sampling. The USAF used RADēCO Model H-809VII samplers at Yokota AB to collect particulate samples. The H-809 is a lightweight sampler with a built-in pressure gauge and can be used with both filter and cartridges. The H-809 is capable of sampling rates from 1 to 8 $ft^3\ min^{-1}$ (RADēCO, 2011a; DOE, 2001).

The USA used RADēCO Model H-810 samplers at Camp Zama and other locations for particulate sampling with filters and for iodine sampling with cartridges. The RADēCO H-810 has an accuracy of 5 percent when run in air volume "totalizer" mode and can be run in total volume mode or total time mode. The RADēCO H-810DC model can operate from 2 to 4 $ft^3\ min^{-1}$, and the DC-N model is capable of 8 to 12 $ft^3\ min^{-1}$ (RADēCO, 2011b). The RADēCO CP-100 cartridge was used to take radioiodine air samples. The CP100 cartridges is a 2.27 inch diameter, 1.04 inch thick TEDA impregnated charcoal cartridge with a size of 40 × 50 mesh and a retention of 99.9 percent. The CP-100 cartridge can be used in tandem with a 47 mm diameter filter paper such as a Whatman cellulose filter, discussed in Section B-4.5 (FRHRM, 2008). Pictures of the RADēCO H-809 and H-810 air samplers are in Figure A-18.

**Figure A-18. RADēCO H-809 and H-810 air samplers**

### A-4.3. Staplex Air Sampler

AIPH used the Staplex TFIA high-volume air sampler to collect air samples at Camp Zama. The TFIA is capable of 0 to 70 $ft^3\ min^{-1}$ and can be used to take 4 inch diameter filter samples or can use an optional filter holder to take 8 inch by 10 inch samples. Typical flow rates are from 7 to 28 $ft^3\ min^{-1}$. (DOE, 2001) A picture of the Staplex TFIA high-volume air sampler is in Figure A-19.


**Figure A-19. Staplex Model TFIA high-volume air sampler**

### A-4.4. F&J Digital Air Sampler

AFRAT and DOE used F&J Specialty Products Model DFHV-1 Digital Air Monitoring System to take air samples. The DFHV-1 can operate in timer mode or total volume mode and can be corrected to standard pressure and temperature. The DFHV-1 system is capable of flow rates of 10 to 38 $ft^3\ min^{-1}$ depending on the filter used and has a flow accuracy rate of 4 percent. (F&J Specialty Products, 2011) A picture of the Model DFHV-1 is in Figure A-20.


**Figure A-20. F&J DFHV-1 air sampler**

### A-4.5. Whatman 41 Cellulose Filter Paper

Some air sample collections were made using Whatman 41 cellulose filter paper. Whatman 41 filter paper has a typical thickness of 220 µm and a basis weight of 85 g $m^{-2}$. Whatman 41 filter paper will remove particles of 20 µm size with 98 percent efficiency (Whatman Inc, undated). Characterizations of Whatman 41 papers for filter have reported efficiencies of 35 to 98 percent for particles of 0.3 to 1.0 µm at face velocities of 1 to 100 cm $s^{-1}$. A picture of a Whatman 41 filter paper is in Figure A-21.


**Figure A-21. Whatman 41 filter paper**

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# Appendix B.

## Potentially Exposed Population Parameters

### B-1. Introduction

This appendix contains a detailed discussion of the DARWG recommended parameter values for radiation dose assessments and the rationales for the selections used for the report for each PEP Category listed in Table B-1. The DARWG recommendations for these parameter values are based almost entirely on what the NCRP calls “subjective and sometimes untestable scientific judgment.” (NCRP, 2009a) Despite this judgment, the DARWG believes that its recommended parameter values are credible values for ingestion and inhalation rates for the purposes of the report.

**Table B-1. PEP categories considered in this report**

<table>
<tr><th>Category*,†</th><th colspan="3">Description</th></tr>
<tr><td rowspan="3">1<br>Adults,<br>Routine<br>Activities</td><td colspan="3">Military members, adults greater than 17 years old, living and working on or near an installation with duties limited to their routine military duties</td></tr>
<tr><td colspan="3">Non-military adults, adults greater than 17 years old, living and working on or near a military installation</td></tr>
<tr><td colspan="3">Non-military adult workers involved in moderate to heavy, outdoor work activities on or near a military installation</td></tr>
<tr><td>2<br>Humanitarian<br>Relief Efforts</td><td colspan="3">Military personnel participating in long-term humanitarian aid missions restricted to one location. This population would be considered to be exposed for the entire OTR exposure duration of 60 days at a location chosen to represent radiation exposure</td></tr>
<tr><td rowspan="7">3–7<br>Children,<br>Routine<br>Activities</td><td colspan="3">Children living on a military installation</td></tr>
<tr><td>PEP Category</td><td>Age Range</td><td>ICRP Dose Coefficient Age</td></tr>
<tr><td>3</td><td>0 to 1 y</td><td>3 months old</td></tr>
<tr><td>4</td><td>>1 y to 2 y</td><td>1 year old</td></tr>
<tr><td>5</td><td>>2 y to 7 y</td><td>5 years old</td></tr>
<tr><td>6</td><td>>7 y to 12 y</td><td>10 years old</td></tr>
<tr><td>7</td><td>>12 y to 17 y</td><td>15 years old</td></tr>
</table>

*The PEP category for individuals on naval vessels at sea and flight crews are not considered here as discussed in Section 3.4.1.

†A PEP for doses to the fetus and infants from the ingestion of mother’s milk will be considered in a future report.

## B-2. Parameter Values used to Calculate Radiation Doses

### B-2.1. Parameter Values for PEP Category 1

The parameter values for PEP Category 1 are discussed in the following sections. It is assumed that there is no accounting for being indoors, i.e., no reduction in external radiation dose and no accounting for lower airborne particulate radioactive material concentrations indoors.

#### *B-2.1.1 Air Inhalation*

***The recommended value for the daily inhalation rate for these populations is 30 $m^3$ $d^{-1}$.***

The daily inhalation rates are based on those for the "heavy worker" (26.8 $m^3$ $d^{-1}$) from ICRP-66 (ICRP, 1994) with an additional two hours of heavy exercise. Table B-2 lists the inhalation rates from ICRP-66 for specific physical activities (ICRP, 1994).

**Table B-2. Activity inhalation rates**

| Activity | Inhalation Rate ($m^3$ $h^{-1}$)* |
|---|---|
| Sleeping | 0.45 |
| Sitting | 0.54 |
| Light Exercise | 1.5 |
| Heavy Exercise | 3 |

*ICRP, 1994

The ICRP defines light exercise as a level of work corresponding to "working in laboratories or workshops, active housekeeping, painting, woodworking etc." (ICRP, 1994) Heavy exercise corresponds to levels of work or exercise as practiced by "firemen, construction workers, farm workers, athletes, etc." for durations of less than two hours (ICRP, 1994). Table B-3 lists the physical activities and inhalation rates used to estimate the recommended value for daily inhalation volume.

Because it is assumed that the PEP contains active-duty military personnel and people engaged in heavy, outdoor work activities, e.g., construction, firefighting, etc., it was assumed that workers were engaged in heavy exercise for three hours of the work day. Furthermore, because physical training is an integral part of military life, an additional hour of heavy exercise was included to account for physical exercise even though the PEP contains non-military members. The DARWG is aware that the ICRP recommends the heavy exercise "is appropriate for periods of time not exceeding 2 h $d^{-1}$," (ICRP, 1994) but given the large military component of this population the DARWG believes that for purposes of estimating values for inhalation rates a maximum 4 hours of heavy exercise is reasonable.

**Table B-3. Activity-based inhalation volumes and daily rates for PEP category 1**

| Activity | Volume Inhaled ($m^3$) |
|---|---|
| Sleeping (8 h) | 3.6 |
| Occupational (8 h)<br>5/8 Light Exercise<br>3/8 Heavy Exercise | 16.5 |
| Non-occupational (8 h)<br>4/8 Sitting<br>3/8 Light Exercise<br>1/8 Heavy Exercise | 9.7 |
| Total Daily Breathing Rate | 29.8 $m^3$ $d^{-1}$ |
| Recommended Value | 30 $m^3$ $d^{-1}$ |

The final recommended value of 30 $m^3$ $d^{-1}$ is about 20 percent greater than the maximum 95$^{th}$ percentile value of 24.6 $m^3$ $d^{-1}$ recommended for adults (> 16 years of age, combined male and female, U.S. population) in the general public in the 2011 Exposure Factors Handbook (EFH) from the U.S. Environmental Protection Agency (EPA, 2011). On an hourly basis, the DARWG recommended value is 1.25 $m^3$ $h^{-1}$, which is slightly larger than the 95$^{th}$ percentile (1.2 $m^3$ $h^{-1}$) of the hourly air intake rate given in NCRP Report 164 (NCRP, 2009b, footnote a to Table 8.12).

#### *B-2.1.2 Drinking Water Ingestion*

***The recommended value for the daily water intake rate for these populations is 4 L $d^{-1}$.***

The maximum 95$^{th}$ percentile drinking water intake rate for adults with ages greater than 21 years from the 2011 EFH is 3.1 L $d^{-1}$ based on data reported by individuals consuming water during the study periods (EPA, 2011). Based on a lognormal distribution and the parameter values from the 2011 EFH the 97.5$^{th}$ percentile for tap water intake is about 3 L $d^{-1}$. (EPA, 2011) In 2008, the U.S Army Combined Arms Support Command published "Potable Water Consumption Planning Factors by Environmental Region and Command Level." (USA, 2008) According to the USA (2008), the requirements for universal unit level drinking water for a conventional theater in temperate climate is 6.2 L $d^{-1}$ (converted from gallons).

Given the range of values for the 95$^{th}$ percentile drinking water intake rate for a U.S. population of adults of 2.6 to 3.1 L $d^{-1}$, the assumption of an increased level of physical activity, and the USA planning factors of about 6.2 L $d^{-1}$, a drinking water intake rate of 4 L $d^{-1}$ seems to be a reasonably conservatively high value for this study.

#### *B-2.1.3 Soil plus Dust Ingestion*

***The recommended value for the soil plus dust ingestion rate for these populations is 200 mg $d^{-1}$.***

In the 2011 EFH, the recommended mean value for the soil plus dust ingestion rate for adults is 50 mg $d^{-1}$. (EPA, 2011) However, the overall confidence in the recommendations is low

and no upper percentile values are given. For children less than 21 years old in the general population, the EPA recommends a 95$^{th}$ percentile value of 200 mg $d^{-1}$. (EPA, 2011) The DARWG recommendation is to use the 95$^{th}$ percentile value of 200 mg $d^{-1}$ from estimates of children's soil plus dust ingestion as a reasonably conservative value for adults for this study.

Pica[15] and geophagy[16] are not considered for adults involved with Operation Tomodachi.

### B-2.2. Parameter Values for PEP Category 2

The parameter values for PEP Category 2 (adults, humanitarian relief) are discussed in the sections below.

#### *B-2.2.1 Air Inhalation*

***The recommended value for the daily inhalation rate for this population is 32 $m^3$ $d^{-1}$.***

The daily inhalation rates are based on the "heavy worker" from ICRP-66 (ICRP, 1994). For adult, humanitarian relief efforts, it is assumed that the workday lasts 12 hours and involves four hours of heavy exercise and eight hours of light exercise. Although the fraction of occupational hours (1/3) spent in heavy exercise is less than that for PEP Category 1 (3/8), the absolute number of hours spent in heavy exercise is the same (four hours). The DARWG believes that given the ICRP's caveat that heavy exercise should last less than two hours (ICRP, 1994) and a review of various inhalation studies in EPA (2011), a reasonable estimate of the maximum absolute length of heavy exercise for this population is four hours.

The final recommended value of 32 $m^3$ $d^{-1}$ is about 30 percent greater than the maximum 95$^{th}$ percentile value of 24.6 $m^3$ $d^{-1}$ recommended for adults (> 16 years of age, combined male and female) in the general public in EPA (2011) and only 7 percent greater than that for PEP Category 1. Table B-4 lists the physical activities and inhalation rates used to estimate the recommended value for daily inhalation.

#### *B-2.2.2 Drinking Water Ingestion*

***The recommended value for the daily water intake rate for this population is 6 L $d^{-1}$.***

The maximum 95$^{th}$ percentile drinking water intake rate for adults > 21 years of age from the 2011 EFH is 3.1 L $d^{-1}$ based on data reported by individuals consuming water during the study periods. (EPA, 2011) Based on a lognormal distribution and the parameter values from the 2011 EFH, the 97.5$^{th}$ percentile for tap water intake is about 3 L $d^{-1}$. (EPA, 2011) According to USA (2008), the requirements for universal unit level drinking water for a conventional theater in temperate climates is 6.2 L $d^{-1}$ (converted from gallons).

Given the range of values for the 95$^{th}$ percentile drinking water intake rate for adults of 2.6 to 3.6 L $d^{-1}$, the USA planning factors of about 6.2 L $d^{-1}$, and the increased physical activities involved with humanitarian relief efforts, a drinking water intake rate of 6 L $d^{-1}$ seems to be a reasonable over estimate for this study.

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[15] Pica is the recurrent ingestion of unusually high amounts of soil (i.e., on the order of 1000-5000 mg/day or more). (EPA, 2011)

[16] Geophagy is the intentional ingestion of earths and is usually associated with cultural practices. (EPA, 2011)

**Table B-4. Activity-based inhalation volumes and daily rates for PEP category 2**

| Activity | Volume Inhaled ($m^3$) |
|---|---|
| Sleeping (8 h) | 3.6 |
| Occupational (12 h)<br>8/12 Light Exercise<br>4/12 Heavy Exercise | 24.0 |
| Non-occupational (4)<br>2/4 Sitting<br>2/4 Light Exercise | 4.1 |
| Total Daily Breathing Rate | 31.7 $m^3$ $d^{-1}$ |
| Recommended Value | 32 $m^3$ $d^{-1}$ |

### *B-2.2.3 Soil plus /Dust Ingestion*

***The recommended value for the soil plus dust ingestion rate for this population is 500 mg $d^{-1}$.***

In the 2011 EFH, the recommended mean value for the soil plus dust ingestion rate for adults is 50 mg $d^{-1}$. (EPA 2011) However, the overall confidence in the recommendations is low and no upper percentile values are given. For children less than 21 years old in the general population, EPA (2011) recommends a 95$^{th}$ percentile value of 200 mg $d^{-1}$. The DARWG's recommendation is to use the 95$^{th}$ percentile value of 200 mg $d^{-1}$ from estimates for children's soil plus dust ingestion as a reasonable over estimate for adults for this study. In addition, the EPA (2011) recommended "high-end" estimate for soil ingestion for children under "Soil-Pica" conditions is 1000 mg $d^{-1}$. Based on these values, the increased intensity and duration of physical activities, and increased availability of loose soil and dust during adult, humanitarian relief activities, the DARWG recommends a soil plus dust ingestion rate for this population of 500 mg $d^{-1}$.

Pica and geophagy are not considered for adults involved with Operation Tomodachi.

## B-2.3. Parameter Values for PEP Categories 3–7 (Children)

The ICRP, in its recommendation for radiological protection, such as ICRP (2001) and EPA in its recommendations regarding exposure assessment for children (EPA, 2011) sort members of the public into different age groups.

Table B-5 provides a comparison of those two sets of criteria for assigning age groups. Table entries are grouped according to the ICRP DC to be applied to the group; for example, the ICRP DC for the 3-month old will be applied to all infants 0 to 1 y of age. The DARWG recommended parameter values are the largest 95$^{th}$ percentile (if available) provided from the equivalent age grouping in EPA (2011); for example, for infants 0 to 1 year of age, the maximum 95$^{th}$ percentile inhalation rate from all of the EPA age groups will be chosen. In no case did an ICRP recommended value exceed a recommended value from EPA (2011).

**Table B-5. Comparison of the ICRP and EPA age groups for members of the public**

| ICRP* | | EPA† |
|---|---|---|
| **Age** | **Age Group** | **Age Group** |
| 3 mo | 0 to 1 y of age | Birth to <1 mo<br>1 to <3 mo<br>3 to <6 mo<br>6 to <12 mo |
| 1 y | >1 y to 2 y | 1 to <2 y |
| 5 y | >2 y to 7 y | 2 to <3 y<br>3 to <6 y |
| 10 y | >7 y to 12 y | 6 to <11 y |
| 15 y | >12 y to 17 y | 11 to <16 y |

*ICRP, 2001; †EPA, 2011

### *B-2.3.1 Air Inhalation*

Table B-6 presents the daily inhalation rates for assessing radiation doses to children as part of the OTR.

**Table B-6. ICRP, EPA, and DARWG recommended daily inhalation rates for children ($m^3\ d^{-1}$)**

| Age | ICRP* | EPA†,‡ | DARWG§ |
|---|---|---|---|
| 3 months | 2.86 | 9.2 | 9.2 |
| 1 y | 5.2 | 12.8 | 12.8 |
| 5 y | 8.76 | 13.8 | 13.8 |
| 10 y | 15.28 | 16.6 | 16.6 |
| 15 y | 20.10 (males)<br>15.72 (females) | 21.9 | 21.9 |

*ICRP, 1994; †EPA, 2011

‡Maximum of the 95th percentiles for an EPA grouping subsumed into the ICRP age groups.

§The DARWG recommendations are the EPA 95th percentile values.

### *B-2.3.2 Drinking Water Ingestion*

Table B-7 presents the daily drinking water ingestion rates for assessing radiation doses to children.

**Table B-7. EPA and DARWG recommended daily drinking water ingestion rates for children (L $d^{-1}$)**

| Age | EPA[*,†] | DARWG[‡] |
|---|---|---|
| 3 mo | 1.2 | 1.2 |
| 1 y | 0.89 | 0.89 |
| 5 y | 1.0 | 1.0 |
| 10 y | 1.4 | 1.4 |
| 15 y | 2.8 | 2.8 |

[*]EPA, 2011
[†]Maximum of the 95th percentiles for an EPA grouping subsumed into the ICRP age groups.
[‡]DARWG recommendations are 95th percentile values from EPA (2011).

### *B-2.3.3 Soil plus Dust Ingestion*

Table B-8 presents the DARWG's recommended daily ingestion rates of soil and dust for assessing radiation doses to children.

**Table B-8. EPA and DARWG recommended daily soil plus dust ingestion rates for children (mg $d^{-1}$)**

| ICRP Dose Coefficient Age | EPA[*,†] | | DARWG |
|---|---|---|---|
| | Age Group | Upper Percentile[‡] | |
| 3 months | 6 to <12 mo | 200[§]/1000[**] | 1000 |
| 1 y | 1 to <6 y | | |
| 5 y | | | |
| 10 y | 6 to <21 y | 200[§]/1000[**] | |
| 15 y | | | |

[*]EPA, 2011
[†]Maximum of the 95th percentiles for an EPA grouping subsumed into the ICRP age groups.
[‡]In the 2011 edition of the EPA's Exposure Factors Handbook (EPA, 2011), the phrase upper percentile is used "to represent values in the upper tail, i.e., between 90th and 99.9th percentile of the distribution of values for a particular exposure factor."
[§]This value is based on the upper percentile value from the 2011 Exposure Factors Handbook (EPA, 2011).
[**]The 2011 Exposure Factors Handbook gives a value of 1000 mg $d^{-1}$ for the upper percentile for "Soil-Pica" conditions, which "it is prudent to assume that, for some children, soil-pica behavior may occur at any age up to 21 years." The upper percentile for geophagy is given as 50,000 mg $d^{-1}$. Geophagy was not considered for this dose assessment.

## B-3. Parameter Values used to Account for Lifestyle Differences

This section provides parameters values for accounting for differences in the effects of spending time indoors and of differing levels of physical activity. The amount of time spent indoors was divided into four groups: none, lower, mean and upper. Five levels of overall physical activity of people were considered: inactive, low activity, medium activity, high activity, and extreme activity. The primary reference for the information in this document is the EPA's 2011 Exposure Factors Handbook (EPA, 2011).

### B-3.1. Parameter Values for Time Spent Indoors

Minimum values (see Table B-9) are chosen from the values for the different EPA age groups for time spent indoors because time spent indoors offers some protection against radiation exposure and the intent in this report is to overestimate the radiation dose if there is any ambiguity.

**Table B-9. Time spent indoors as a function of age**

| ICRP[*] | | EPA[†] | Time Spent Indoors (minutes per day) | | | |
|---|---|---|---|---|---|---|
| **Age** | **Age Group** | **Age Group** | **None** | **Lower[‡]** | **Mean[§]** | **Upper[**]** |
| 3 mo | 0 to 1 y | Birth to <1 mo<br>1 to <3 mo<br>3 to <6 mo<br>6 to <12 mo | 0 | 579 | 1108 | 1440 |
| 1 y | >1 y to 2 y | 1 to <2 y | 0 | 579 | 1065 | 1440 |
| 5 y | >2 y to 7 y | 2 to <3 y<br>3 to <6 y | 0 | 523 | 957 | 1296 |
| 10 y | >7 y to 12 y | 6 to <11 y | 0 | 458 | 893 | 1275 |
| 15 y | >12 y to 17 y | 11 to <16 y | 0 | 415 | 889 | 1315 |
| Adult | >17 y | 16 to <21 y<br>18 to <65 y<br>>65 y | 0 | 330 | 833 | 1288 |

[*]ICRP, 2001
[†]EPA, 2011
[‡]The lower bound for the time spent indoors is the minimum value of the 5th percentile of the time spent sleeping/napping for the EPA age group (EPA, 2011, Table 16-25 for children and Table 16-26 for adults).
[§]Minimum value of the 50th percentile for the EPA age group (EPA, 2011, Table 16-1).
[**]Minimum value of the 95th percentile for the EPA age group (EPA, 2011, Table 16-1).

### B-3.2. Parameter Values for Levels of Physical Activity

The levels of physical activity and the percentile value of the parameters of concern considered were: inactive (25th percentile), low activity (50th percentile or central tendency), medium activity (75th percentile), high activity (95th or "upper percentile"), and extreme activity (modified 95th or upper percentile values to account for adult, humanitarian relief efforts). These levels of physical activity are used in the selection of values for breathing rates as a function of

age (Table B-10), water ingestion rates as a function of age (Table B-11), and soil ingestion rates as a function of age (Table B-12).

**Table B-10. Breathing rates as a function of ICRP age**

| ICRP Age | Breathing Rates ($m^3\ d^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Inactive* | Low Activity† | Medium Activity‡ | High Activity§ | Extreme Activity** (Humanitarian Relief) |
| 3 months (0.22 to 1 y) | 3.69 | 4.22 | 4.75 | 9.2 | NA |
| 1 y (1 to 2 y) | 4.53 | 5.12 | 5.71 | 12.8 | |
| 5 y (2 to 5 y) | 7.81 | 8.64 | 10.21 | 13.8 | |
| 10 y (7 to 11 y) | 9.25 | 10.59 | 11.94 | 16.6 | |
| 15 y (11 to 23 y) | 14.75 | 17.23 | 19.70 | 21.9 | |
| Adults (23 to 96 y) | 15.59 | 17.48 | 19.38 | 30.0 | 32.0 |

*These breathing rates are maximum value of the 25th percentile values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 6-4).

†These breathing rates are maximum value of the 50th percentile values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 6-4).

‡These breathing rates are maximum value of the 75th percentile values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 6-4).

§These breathing rates are the based on 95th or upper percentile values from the EPA (2011) and are discussed in Section B-2.1.

**These breathing rates are the based on 95th or upper percentile values from the EPA (2011) and are discussed in Section B-2.2.

**Table B-11. Drinking water ingestion rates as a function of ICRP age**

| ICRP Age | Drinking Water Ingestion Rates (L $d^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Inactive* | Low Activity† | Medium Activity‡ | High Activity§ | Extreme Activity** (Humanitarian Relief) |
| 3 months (0 to 1 y) | 0.384 | 0.612 | 0.851 | 1.2 | NA |
| 1 y (1 to 2 y) | 0.159 | 0.294 | 0.481 | 0.89 | |
| 5 y (2 to 6 y) | 0.255 | 0.442 | 0.682 | 1.0 | |
| 10 y (6 to 11 y) | 0.310 | 0.506 | 0.805 | 1.4 | |
| 15 y ( 11 to 16 y) | 0.404 | 0.665 | 1.105 | 2.8 | |
| Adults (>16 y) | 0.939 | 1.345 | 1.877 | 4.0 | 6.0 |

*These ingestion rates are maximum value of the 25th percentile values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 3-18).

†These ingestion rates are maximum value of the 50th percentile values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 3-18).

‡These ingestion rates are maximum value of the 75th percentile values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 3-18).

§These ingestion rates are the based on 95th or upper percentile values from the EPA (2011) and are discussed in Section B-2.1.

**These ingestion rates are the based on 95th or upper percentile values from the EPA (2011) and are discussed in Section B-2.2.

**Table B-12. Soil ingestion rates as a function of ICRP age**

| ICRP Age | Soil Ingestion (mg $d^{-1}$) | | | | |
|---|---|---|---|---|---|
| | Inactive* | Low Activity† | Medium Activity‡ | High Activity§ | Extreme Activity** (Humanitarian Relief) |
| 3 months ( 6 wks to 1 y) | 16.8 | 60 | 200 | 1000 | NA |
| 1 y (1 to 6 y) | 16.8 | 100 | 200 | 1000 | |
| 5 y (1 to 6 y) | 16.8 | 100 | 200 | 1000 | |
| 10 y (6 to 21 y) | 16.8 | 100 | 200 | 1000 | |
| 15 y (6 to 21 y) | 16.8 | 100 | 200 | 1000 | |
| Adults (>21 y) | 16.8 | 100 | 200 | 200 | 500 |

*These ingestion rates are maximum value of the 25th percentile values reported in Table 5-22 of the 2011 Exposure Factors Handbook (EPA, 2011). This value is based on a simulation for ages 3 to < 6 years of age.

†These soil plus dust ingestion rates are "general population central tendency" values for the EPA age groups subsumed into the ICRP age groups (EPA, 2011, Table 5-1).

‡These soil plus dust ingestion rates are "general population upper percentile" values recommended by EPA (2011, Table 5-1)

§These breathing rates are the based on 95th or upper percentile values from the EPA (2011) and are discussed in Section B-2.1.

**These breathing rates are the based on 95th or upper percentile values from the EPA (2011) and are discussed in Section B-2.2.

# Appendix C.

## Calculations and Data Usage

### C-1. General Discussion

For the purposes of this radiation dose assessment, external and internal radiation doses were calculated and summed to provide a total effective dose (TED) to the whole body and a total equivalent dose to the thyroid.

External exposure was measured by fixed and portable instruments in the field. Most fixed measurements were made by GOJ at MEXT stations at heights ranging from approximately 1 to 40 meters above the ground. Most DOD measurements were taken with portable radiation detection instruments at a height of approximately 1 meter. External exposure measurements included contributions from exposures during cloud immersion as well as exposure to radionuclides deposited on the ground and other surfaces. Detailed discussions of the instruments used and the measurements taken can be found in Section 2 and Appendix A of this report.

Pathways considered for intake of radionuclides included inhalation of contaminated air, ingestion of contaminated water, and ingestion of contaminated soil and dust. The measured air concentrations include contributions from a passing plume of radioactive material and from resuspended radioactive material previously deposited from passing plumes. To provide an overestimate of radioactive materials in water, all water consumed was assumed to come from local surface reservoirs, and no reductions in radionuclide intake were made for those drinking bottled water or water from deep-well sources, which would have not become contaminated immediately. Conservative breathing and ingestion rates discussed in Section 3 were used. The potential for internal dose from contaminated food was considered negligible as discussed in Section 2.7.

Doses from external radiation were calculated as the equivalent doses ($H_T$) for organs and effective doses (E) for whole body. Internal radiation doses were calculated as committed equivalent doses ($H_{T,\tau}$) for organs and committed effective doses ($E(\tau)$) for the whole body. Representative units on parameters used in equations in this appendix are shown in parentheses to provide the reader with a greater understanding of the physics and calculations.

All calculations were done on an hourly basis and summed over the 60-day period from March 12 through May 11, 2011 to yield the total dose over the period. Measurements were either taken hourly or daily. If only daily measurements were made then hourly values were calculated by dividing the daily value by 24 hours. Measurements were taken in mixed SI and traditional units. All measurements were used in the form they were taken in and then converted to the traditional units used by DOD as part of the calculation of dose. This was done to reduce unit conversion errors and to more readily facilitate peer review of the calculations. Typically, traditional units for DOD include activities measured in curies, exposures measured in roentgens, absorbed doses measured in rad, and equivalent and effective doses reported in rem.

Calculations were performed for 13 shore locations and for each PEP category that was applicable at each location. All locations did not include every PEP category. For example,

Sendai Airport did not have the child-related PEP categories. The shore locations and distances from each site to the nearest MEXT station are listed in Table 24 of Section 2 of this report. This list actually includes an additional shore site, J-Village, for which there were no environmental data available to perform calculations. J-Village was in the hot zone and DOD-affiliated individuals only worked there for short periods, and those who visited there were provided with personnel dosimeters. A dose estimate at this site will be calculated based on the available dosimeter and internal monitoring measurements.

These dose calculations have been automated by the use of macro scripts inside MS Excel spreadsheets. The use of macro-assisted spreadsheets was chosen for practical considerations. They offer an intuitive, time saving, and cost effective way to build a peer-reviewable dose calculation. One spreadsheet was created for each of the 13 locations for which environmental data were available. For each location, dose calculations were performed for thyroid dose, thyroid committed equivalent dose, whole body effective dose, and whole body committed effective dose for each PEP. The number of potential PEPs (1,261) is calculated by multiplying the number of PEP categories (97) by the number of locations (13). For this report the number of PEP categories is calculated based on the lifestyle parameters discussed in Appendix B, as follows: (6 age categories) × (4 activity level categories) × (4 time indoors categories) + (1 humanitarian relief category) = 97. The word "potential" was used because not every location had all age categories present. However, the spreadsheet calculated all age groups and the inapplicable ones where filtered out during reporting of the initial dose values, since it was easier to program the macros without the filtering. Each spreadsheet is about 22 megabytes in size and requires over two minutes to process a single run of data for a single organ at one location on an MS Windows-based, personal computer system. The spreadsheets are very modular in design with separate tabs used for control functions, reporting outputs, PEP definitions, measurement data, DCs, and calculations. The first tab on each spreadsheet describes its use, structure, and historical changes with each version.

## C-2. Whole Body Total Effective Dose (TED)

Equations C-1 and C-2 summarize the TED calculation.

$$T\dot{E}D = \dot{E}_{\gamma} + E(\dot{\tau})_{Inh} + E(\dot{\tau})_{W} + E(\dot{\tau})_{S} \tag{C-1}$$

where:

| | | |
|---|---|---|
| $T\dot{E}D$ | = | total whole body effective dose rate (rem $hr^{-1}$) |
| $\dot{E}_{\gamma}$ | = | effective dose rate from external radiation (rem $hr^{-1}$) |
| $E(\dot{\tau})_{Inh}$ | = | committed effective dose rate from inhalation (rem $hr^{-1}$) |
| $E(\dot{\tau})_{W}$ | = | committed effective dose rate from water ingestion (rem $hr^{-1}$) |
| $E(\dot{\tau})_{S}$ | = | committed effective dose rate from soil ingestion (rem $hr^{-1}$) |

$$TED = \sum_{j=1}^{1440} T\dot{E}D_j \qquad \text{(C-2)}$$

where:

| | | |
|---|---|---|
| $TED$ | = | total whole body effective dose summed over all hours $j$ in the 60-day period March 12 through May 11, 2011 (rem) |

Dots are used above variable names to indicate that a rate of that quantity is being used. Each of the parameters in Equation C-1 is expanded in Equations C-4 through C-8 and discussed in the paragraphs that follow. As will be shown, the committed effective doses listed in Equation C-1 were calculated for individually identified nuclides and then summed to yield a total committed effective dose for each of the three pathways listed (air inhalation, water ingestion, and soil and dust ingestion).

The radionuclides chosen for the internal dose calculations are listed in Table C-1 and are based on spectrometric measurements made by DOD, DOE, and GOJ. Although air concentrations of elemental iodine at the distances of the 13 DARWG locations from FDNPS were assumed to make no significant contribution to dose as discussed in OECD (2007), the gaseous component of airborne iodine was assigned to one part elemental iodine and two parts organic iodine (methyl iodine) for additional conservatism.

### C-3. Whole Body Effective Dose Rate from External Radiation

The whole body effective dose rate from external radiation exposure is calculated using Equation Error! Reference source not found., with explanation of each term following in the paragraphs below the equation.

$$\dot{E}_\gamma = \dot{X} \times Q \times IDRFE \qquad \text{(C-3)}$$

where:

| | | |
|---|---|---|
| $\dot{E}_\gamma$ | = | effective dose rate from external radiation (rem hr$^{-1}$) |
| $\dot{X}$ | = | external radiation exposure rate measurement (R hr$^{-1}$) |
| $Q$ | = | dose per exposure conversion factor (rem R$^{-1}$) |
| $IDRFE$ | = | indoor dose reduction factor for external radiation (no units) |

For all locations, values for $\dot{X}$ in Equation C-3 were either available or could be estimated from measurements at MEXT stations whose distances to the point of interest ranged from 0 to 44 miles (See Table 24). The varied instruments, measurement techniques, and physical locations associated with DOD, DOE, and GOJ methods resulted in some variation among these measurements. As stated previously, a detailed discussion of the instruments used and the measurements taken can be found in Section 2 and Appendix B of this report.

As an approximation, $Q$ in Equation C-3 was conservatively assumed to be unity for all calculations. This was based on an observation that the energy dependent conversion factors listed in Table C-2 and Table C-3 are about one or less for all energies.

**Table C-1. Radionuclides included in calculations of hourly internal dose**

| Air Inhalation*† | Water Ingestion* | Soil Ingestion* |
|---|---|---|
| Ba-140 ($t_{1/2}$= 12.78 d)<br>Cs-134 ($t_{1/2}$= 2.05 y)<br>Cs-136 ($t_{1/2}$= 13.70 d)<br>Cs-137 ($t_{1/2}$= 30.0 y)<br>I-130‡ ($t_{1/2}$= 0.51 d)<br>I-131 ($t_{1/2}$= 8.04 d)<br>I-132 ($t_{1/2}$= 0.09 d)<br>I-133 ($t_{1/2}$= 0.84 d)<br>La-140 ($t_{1/2}$= 40.18 d)<br>Rb-86 ($t_{1/2}$= 18.63 d)<br>Mo-99 ($t_{1/2}$= 2.78 d)<br>Tc-99m ($t_{1/2}$= 2.78 d)<br>Te-129 ($t_{1/2}$= 0.05 d)<br>Te-129m ($t_{1/2}$= 33.97 d)<br>Te-131m ($t_{1/2}$= 0.02 d)<br>Te-132 ($t_{1/2}$= 3.25 d)<br>Sr-89§ ($t_{1/2}$= 52.60 d)<br>Sr-90§ ($t_{1/2}$= 27.70 y) | I-131 ($t_{1/2}$= 8.04 d)<br>Cs-134 ($t_{1/2}$= 30.0 y)<br>Cs-137 ($t_{1/2}$= 2.05 y) | I-131 ($t_{1/2}$= 8.04 d)<br>Cs-134 ($t_{1/2}$= 2.05 y)<br>Cs-136 ($t_{1/2}$= 13.70 d)<br>Cs-137 ($t_{1/2}$= 30.0 y)<br>Te-132 ($t_{1/2}$= 3.25 d) |

*Hourly or daily measurements were obtained for radionuclides listed except where noted.
†All radionuclides are in aerosol form except radioiodines, which may be present in gaseous or aerosol forms. The hourly values for gaseous radioiodine were calculated by multiplying the corresponding aerosol concentration by 2.51, a factor determined from DOD airborne activity concentration measurements on 12 days during March 16 through April 30, 2011 at Yokosuka NB, Yokota AB, and the U.S. Embassy. Gaseous iodines consist of 1/3 elemental form and 2/3 organic form (methyl iodide).
‡Although I-130 is not a fission product, it is produced by neutron activation in a power reactor in sufficient quantities, and it was measured in air samples.
§The hourly values for these radionuclides were calculated by multiplying the Cs-137 air activity concentration by 0.00053. This factor is the mean value (n = 15) of the Sr-90 to Cs-137 ratio taken from a set of soil analyses from a May 31, 2011 MEXT soil analysis report (GOJ, 2011a).

In Equation C-3, $IDRFE$ is a multiplication factor that reduces the external radiation dose rate proportionately to the time spent indoors and to the dose reduction factor for external radiation (DRFE), which is the fractional reduction in external radiation exposure by being indoors. The DRFE accounts for the fact that buildings reduce the external radiation exposure to people inside them from the radiation from sources outside the building due to the attenuation of the radiation by the shielding properties of construction materials, and by the reduction of radiation exposure rate due to the standoff distances between the people and the external sources of radiation. Typical literature values provide a DRFE of 0.50 for buildings. The relationship

between IDRFE and the DRFE as a function of the time in minutes spent indoors ($T_{IN}$) is shown by Equation C-4.

**Table C-2. Variation of the effective dose with age for irradiation from a volume source in the air**

| Source Energy (MeV) | Conversion Factor (Sv Gy$^{-1}$ and rem rad$^{-1}$) | | |
|---|---|---|---|
| | Baby (8 Weeks) | Child (7 years) | Adult |
| 0.015 | 0.027 | 0.016 | 0.012 |
| 0.020 | 0.074 | 0.041 | 0.033 |
| 0.030 | 0.287 | 0.173 | 0.129 |
| 0.040 | 0.533 | 0.342 | 0.264 |
| 0.050 | 0.679 | 0.481 | 0.384 |
| 0.060 | 0.765 | 0.571 | 0.474 |
| 0.070 | 0.824 | 0.643 | 0.542 |
| 0.080 | 0.843 | 0.676 | 0.584 |
| 0.100 | 0.853 | 0.713 | 0.626 |
| 0.150 | 0.873 | 0.745 | 0.657 |
| 0.200 | 0.836 | 0.741 | 0.655 |
| 0.300 | 0.862 | 0.754 | 0.66 |
| 0.500 | 0.853 | 0.759 | 0.679 |
| 0.700 | 0.868 | 0.781 | 0.689 |
| 1.000 | 0.866 | 0.779 | 0.701 |
| 1.500 | 0.913 | 0.823 | 0.727 |
| 2.000 | 0.894 | 0.857 | 0.747 |
| 3.000 | 0.945 | 0.884 | 0.775 |
| 6.000 | 0.964 | 0.92 | 0.828 |
| 10.000 | 0.973 | 0.901 | 0.842 |

Saito et al., 1998.

$$IDRFE = 1 - \left(DRFE \times \frac{T_{IN}}{1440}\right) \qquad \text{(C-4)}$$

where:

| | | |
|---|---|---|
| $IDRFE$ | = | indoor dose reduction factor for external radiation (no units) |
| $DRFE$ | = | Dose reduction factor for external radiation (no units) |
| $T_{IN}$ | = | time spent indoors (min) |
| $1440$ | = | number of minutes in a day |

**Table C-3. Variation of the effective dose with age for irradiation from a plane source on the ground**

| Source Energy | Conversion Factor (Sv $Gy^{-1}$ and rem $rad^{-1}$) | | |
|---|---|---|---|
| (MeV) | Baby (8 Weeks) | Child (7 years) | Adult |
| 0.015 | 0.038 | 0.032 | 0.011 |
| 0.020 | 0.105 | 0.061 | 0.033 |
| 0.030 | 0.373 | 0.193 | 0.132 |
| 0.040 | 0.656 | 0.409 | 0.294 |
| 0.050 | 0.848 | 0.592 | 0.452 |
| 0.060 | 0.951 | 0.716 | 0.576 |
| 0.070 | 1.013 | 0.804 | 0.661 |
| 0.080 | 1.033 | 0.838 | 0.709 |
| 0.100 | 1.031 | 0.868 | 0.739 |
| 0.150 | 1.006 | 0.848 | 0.745 |
| 0.200 | 0.997 | 0.823 | 0.736 |
| 0.300 | 0.995 | 0.810 | 0.716 |
| 0.500 | 0.986 | 0.813 | 0.727 |
| 0.700 | 1.009 | 0.839 | 0.751 |
| 1.000 | 1.013 | 0.839 | 0.755 |
| 1.500 | 1.008 | 0.862 | 0.790 |
| 2.000 | 1.019 | 0.878 | 0.816 |
| 3.000 | 1.022 | 0.907 | 0.850 |
| 6.000 | 1.031 | 0.898 | 0.872 |
| 10.000 | 1.011 | 0.897 | 0.880 |

Saito et al., 1998.

Table B-9 shows the assumed amounts of time spent indoors for each age group for each of four categories (none, lower, mean, upper) used in the calculations in this report. Using the values in Table B-9 in Equation C-4 yields the IDRFE shown in Table C-4.

**Table C-4. Indoor reduction factors for external radiation**

| ICRP Age Group | IDRFE Values for Categories of Time Spent Indoors* | | | |
|---|---|---|---|---|
| | None | Lower | Mean | Upper |
| 3 mo | 1.000 | 0.799 | 0.615 | 0.500 |
| 1 y | 1.000 | 0.799 | 0.630 | 0.500 |
| 5 y | 1.000 | 0.818 | 0.668 | 0.550 |
| 10 y | 1.000 | 0.841 | 0.690 | 0.557 |
| 15 y | 1.000 | 0.856 | 0.691 | 0.543 |
| Adults | 1.000 | 0.885 | 0.711 | 0.553 |

*See Appendix B for definitions.
IDRFE for DRFE=0.50 for Time Spent Indoors from Table B-9

Thatcher et al. (2001) states that the average amount of time spent indoors by individuals in the U.S. is estimated to be greater than 75 percent (18 hours/day). Also, this amount of time spent indoors or more would be likely for most persons in Japan during the months of March through May because these are winter/spring months with cooler temperatures. For example, mean temperatures around the Tokyo area range from 47 to 66 degrees Fahrenheit from March through May (see Table C-5).

Business rules were developed to combine datasets of external radiation measurements from different sources to yield a consistent, technically based set of measurements.

First, background radiation levels based on external radiation rates measured by the GOJ prior to the March 11, 2011 accident were subtracted from all later measurements for the same location. Background levels were subtracted to produce a calculated whole body effective dose that would represent the contribution from the FDNPS accident. The pre-accident background radiation existed prior to and after March 11, 2011, and was considered part of the dose that each person gets as a result of living on the earth at that location; therefore, the DARWG decided it should not be included in the resulting doses.

Second, for each location for each hour of the day a selection priority was used to combine DOD, DOE, or MEXT external radiation rate data. For every hour with a DOD or DOE measurement, the highest measurement for that hour was used. This priority was based on recognition that DOD and DOE measurements were obtained at locations closer to the location of interest and were associated with instruments whose measurement capabilities were known.

**Table C-5. Temperature and precipitation monthly averages for Tokyo, Japan***

| Low | Average Low | Mean | Average High | Average Precipitation (inches) |
|---|---|---|---|---|
| Jan | 34°F | 42°F | 49°F | 1.8 |
| Feb | 35°F | 42°F | 49°F | 2.4 |
| Mar | 39°F | 47°F | 54°F | 3.9 |
| Apr | 50°F | 57°F | 64°F | 4.9 |
| May | 58°F | 66°F | 73°F | 5.4 |
| Jun | 65°F | 71°F | 77°F | 7.3 |
| Jul | 72°F | 78°F | 83°F | 5.0 |
| Aug | 75°F | 81°F | 87°F | 5.8 |
| Sep | 68°F | 74°F | 80°F | 7.1 |
| Oct | 57°F | 64°F | 70°F | 6.5 |
| Nov | 48°F | 55°F | 61°F | 3.5 |
| Dec | 39°F | 46°F | 53°F | 1.8 |

*Weather.com, 2012

Third, when DOD or DOE data were unavailable at a location for a particular hour, adjusted GOJ MEXT data were used. It should be noted that the GOJ states on the bottom of their reports that $\mu Gy\ h^{-1} = \mu Sv\ h^{-1}$ and they state on their website that in emergencies they assume that values of exposure, dose, and dose equivalent are numerically equal for their external radiation measurements. The MEXT data were adjusted with a multiplicative factor that ranged between 1.33 and 5.12 (with a mean value over the 13 sites of 3.57, with a CV of 32 percent) because DOD and DOE exposure rate measurements were consistently higher than the MEXT measurements. Possible explanations of this observation are provided in Section 2.3 of this report. The numerical value of the MEXT adjustment factor for a particular location was determined by averaging the ratios of available measurements between DOD or DOE data with the MEXT data. For Sasebo NB, the standard adjustment factor from the 60-day report was used. As a side analysis, the adjustment factor was also calculated using a least squares fit, and the result agreed with the arithmetic mean of the ratios to within less than 10 percent.

For 11 of the 13 external dose calculations, 1440 data points of MEXT data were used. For Sendai Airport and City of Ishinomaki, 1100 data points of MEXT data were used because that monitoring station was off-line for 112 hours at the beginning of the 60-day OTR period, and also off-line from 1700 March 17 to 1700 March 28. The numbers of DOD and DOE dataset points used are shown in Table 26.

External radiation rate data were fit using a linear interpolation function between known data points to determine an hourly external radiation rate. Since pre-accident external radiation rates were subtracted, there were exposure rates at some hours with negative values due to the low external radiation levels and slight variability of measurements. All negative values of net external radiation rate were set to zero, thus further ensuring that a dose was calculated.

## C-4. Committed Effective Dose Rate from Air Inhalation

The committed effective dose rate from air inhalation is calculated using Equation C-5. Explanations of each term follow in the paragraphs below the equation.

$$\dot{E(\tau)}_{Inh} = \dot{B} \times DF \times 10^{-4} \times \sum_{i=1}^{22} \left( AA_i \times DC_{Eff,Inh_i} \times IDRFI_i \right) \quad \text{(C-5)}$$

where:

| | | |
|---|---|---|
| $\dot{E(\tau)}_{Inh}$ | = | committed effective dose rate from inhalation (rem $hr^{-1}$) |
| $\dot{B}$ | = | volume of air breathed per hour ($m^3$ $h^{-1}$) |
| $DF$ | = | sample time decay correction factor (no units) |
| $10^{-4}$ | = | units conversion factor (Bq $\mu Bq^{-1}$ rem $Sv^{-1}$) |
| $AA_i$ | = | measured air activity per air volume for species *i* ($\mu$Bq $m^{-3}$) |
| $DC_{Eff,Inh_i}$ | = | inhalation effective dose coefficient for species *i* (Sv $Bq^{-1}$) |
| $IDRFI_i$ | = | indoor dose reduction factor for inhalation for species *i* (no units) |

Equations C-8 and C-9 provide additional calculations for $AA_i$ for organic iodine vapors, and for strontium aerosols.

In Equation C-5, values for the $\dot{B}$ for each PEP are derived from values shown in Section 3 of this report. The daily value was divided by 24 hours to facilitate hourly calculations performed in the spreadsheet.

In Equation C-5, *IDRFI* is a multiplication factor that reduces the committed effective dose rate from inhalation proportionally to the time spent indoors and to the dose reduction factor for inhalation (DRFI). The DRFI is the fractional reduction in air activity concentrations of aerosols afforded by being inside a building. Indoor air environments of buildings provide some reduction in aerosol concentrations of radiological contaminants that have an outdoor origin, such as the radiological contaminants released during this reactor accident.

Many factors influence the relationship between indoor airborne concentrations and outdoor concentrations. Important factors include intentional air exchange by mechanical ventilation systems, status of operable doors and window, e.g., closed or open, indoor activity levels, indoor deposition velocities of aerosols, ventilation system filtration, and the relative air-tightness of the building. Current radiological accident models assume a DRFI of 0.50 for indoor residence during the outdoor passage of a radioactive aerosol cloud (Fogh et al., 1997). In this case, the DRFI is the ratio of indoor to outdoor air concentrations, integrated from the time of initial cloud passage to infinity. Fogh et al. (1997) performed experimental studies to assess DRFIs on test homes, conducted a select review of previous measurements of DRFI, and modeled DRFI across a range of test room sizes and aerosol characteristics. The results support a DRFI of 0.50 for iodines in particulate form for an average home, with lower DRFIs for other

volatile elements (Cs, Ru), and refractory elements (Pu, Sr). It is important to note that the DRFIs are assumed to be not applicable to gases, which for this accident pertain to noble gases and gaseous forms of iodine. Therefore, the IDRFI will be one for gaseous iodine species and less than one for all other species since all others are aerosols. This is why the IDRFI is inside the summation term in Equation C-5. The value of IDRFI for all aerosols is related to the DRFI and the minutes spent indoors as shown by Equation C-6.

$$IDRFE = 1 - \left(DRFE \times \frac{T_{IN}}{1440}\right) \qquad \text{(C-6)}$$

where:

| | | |
|---|---|---|
| $IDRFI$ | = | indoor dose reduction factor for internal radiation (no units) |
| $DRFI$ | = | dose reduction factor for inhalation (no units) |
| $T_{IN}$ | = | time spent indoors (min) |
| $1440$ | = | number of minutes in a day |

Table B-9 listed the minutes for the four categories of time spent indoors for each age group, which were used in Equation C-5 to calculate *IDRFI* values as listed in Table C-6.

**Table C-6. Indoor reduction factor for air inhalation**

| **ICRP Age Group** | **IDRFI Values* for Categories of Time Spent Indoors†** | | | |
|---|---|---|---|---|
| | **None** | **Lower** | **Mean** | **Upper** |
| 3 mo | 1.000 | 0.799 | 0.615 | 0.500 |
| 1 y | 1.000 | 0.799 | 0.630 | 0.500 |
| 5 y | 1.000 | 0.818 | 0.668 | 0.550 |
| 10 y | 1.000 | 0.841 | 0.690 | 0.557 |
| 15 y | 1.000 | 0.856 | 0.691 | 0.543 |
| Adults | 1.000 | 0.885 | 0.711 | 0.553 |

*IDRFI calculated for DRFI=0.50 with Time Spent Indoors from Table B-9. IDRFI for gases is 1.0 because there is no protection provided.
†See Appendix B for definitions.

In Equation C-5, the *sample time decay correction factor* term corrects for the decay that occurs during sampling. For each nuclide, correction factors were applied to account for the physical decay that occurs during the time it takes to perform the collection of air according to Equation C-7.

$$DF = \frac{\left[\ln(2)/t_{1/2}\right] \times T}{\left[1 - e^{-\left[\ln(2)/t_{1/2}\right] \times T}\right]} \tag{C-7}$$

where:

| | | |
|---|---|---|
| $DF$ | = | sample time decay correction factor (no units) |
| $t_{1/2}$ | = | radioactive half-life ($h^{-1}$) |
| T | = | sampling time (h) |

Values for $DF$ ranged from approximately 1.0 for 5-minute samples to 40.3 for a 24-hour sample (for Te-131m with $t_{1/2} = 0.4$ h).

In Equation C-5, values for the measured activity per air volume term were obtained from the laboratory analyses of filter media and activated charcoal cartridges. Aerosol and gaseous forms of iodine were considered in the air inhalation calculation of committed effective dose. For all other nuclides only aerosol forms were considered. For gaseous iodine, both elemental iodine and methyl iodide were considered. While air sampling and analysis methods used were not capable of differentiating the chemical form of gaseous I-131, the DARWG concluded based on a review of Nair et al. (2000) and OECD (2007) that for air sampling at long distances from the reactor, i.e., ~ 145 miles for the U.S. Embassy and Yokota AB, the vast majority of the gaseous I-131 would be in organic chemical form vice elemental. Although DARWG believes that gaseous iodine is almost entirely in organic form, to account for the facts that the DCs for elemental iodine are higher than those for organic form, the DARWG conservatively assumed that one-third of the gaseous I-131 was in an elemental form and two-thirds in the organic form. The same assumption was applied to the other isotopes of iodine.

Aerosol particles were assumed to be represented by a 1.0 µm AMAD; an assumption based on studies of particle size from the Chernobyl accident (Dorrian, 1997; ICRP, 1994). It was assumed that only aerosols were captured on filter media and only gases on activated charcoal cartridges. The filter media could have captured some elemental iodine, which would be included with the aerosol iodine for the dose calculations. Sampling at many locations used only filter media. Therefore, to be able to estimate air activity concentrations for gaseous iodine at all locations a multiplicative factor was applied to the air activity concentration of aerosol iodine. The same factor was used on all four isotopes of iodine considered (I-130, I-131, I-132 and I-133). The mean value of the ratio of time-weighted gas concentrations to time-weighted aerosol concentrations at the U.S. Embassy data was determined to be $1.88 \pm 0.32$ (1 σ). The DARWG used the upper 95 percent confidence value ($2.507 = 1.88 + [1.96 \times 0.32]$) of this ratio to estimate to concentrations of gaseous iodine. ICRP (2001) contains DCs for gaseous iodine in elemental and organic (methyl iodide) chemical forms as shown in Table 12 of this report. The whole body effective and thyroid organ DCs are about 27 percent higher for the elemental chemical form compared to the organic form with a small amount of variability among the various age groups. The air activity concentration measurements were made on filter canisters with and without charcoal to determine the gas to aerosol ratio. There were measurements on 12 days during the period March 26 through April 27, 2011. Equation C-8 shows the calculation

of gaseous iodine; the three terms in the summation in Equation C-5 are replaced with the right-hand side of Equation C-8 for the gaseous iodine terms.

$$IDF_i = AA_{1-aero_i} \times 2.507 \times \left[\left(DC_{Eff,Inh,MI_i} \times \frac{2}{3}\right) + \left(DC_{Eff,Inh,MI_i} \times \frac{1}{3}\right)\right] \qquad \text{(C-8)}$$

where:

| | | |
|---|---|---|
| $IDF_i$ | = | iodine dose factor for gaseous iodine isotopes (µBq Sv Bq$^{-1}$ m$^{-3}$) |
| $AA_{I-aero_i}$ | = | measured air activity for aerosol iodine isotope *i* (µBq m$^{-3}$) |
| 2.507 | = | gaseous iodine to aerosol iodine factor (no units) |
| $DC_{Eff,Inh,MI_i}$ | = | inhalation effective dose coefficient for methyl iodine *i* (Sv Bq$^{-1}$) |
| $DC_{Eff,Inh,EI_i}$ | = | inhalation effective dose coefficient for elemental iodine *i* (Sv Bq$^{-1}$) |

As shown in Equation C-9, air activity concentrations for Sr-89 and Sr-90 were calculated by multiplying the Cs-137 air activity concentration by a factor equal to 0.00053. This factor was chosen based on a MEXT soil analysis report dated May 31, 2011 for samples taken for Sr-90 from March 16 to May 6, 2011 at locations in Fukushima Prefecture and are assumed to be the same fraction as for Sr-89 based on cumulative fission yields (England and Rider, 1994; IAEA, 2000). These samples were analyzed by the Japan Chemical Analysis Center (GOJ, 2011a).

$$AA_{Sr} = AA_{Cs137} \times 0.00053 \qquad \text{(C-9)}$$

where:

| | | |
|---|---|---|
| $AA_{Sr}$ | = | air activity for aerosol strontium isotopes (µBq m$^{-3}$) |
| $AA_{Cs137}$ | = | measured air activity of Cs-137 (µBq m$^{-3}$) |
| 0.00053 | = | Sr–to–Cs-137 air activity factor (unitless) |

For environmental data used in this radiation dose assessment, many assumptions and interpretations had to be made due to the many different sources of data and variations in methods for taking the data by DOD, DOE, and GOJ. Some locations had very limited data that only covered a few days while other locations had multiple results per day for many days of the 60-day period.

For locations and days with multiple air activity concentration measurements, the arithmetic mean of the measurements was used as the single value for that day. Shorter and longer sampling times were treated equally and a weighted mean based on sampling time was not performed. Also, measurements were assigned to a particular day using the start of sampling time and day, even if the sampling continued to the next day and even if the majority of the time

spent sampling fell on the next day. These simplifications are not expected to produce significant changes in the measured values or doses calculated.

Another issue with air concentration data was that some DOD entities only analyzed samples for iodine and cesium. Ratios were calculated from samples that were analyzed for all significant isotopes, and the ratios were used to account for the missing isotopes for those samples. To estimate air concentrations for missing isotopes in dose calculations, ratios were calculated using an arithmetic mean of the air concentration data measured at the IMS Takasaki and at Yokota AB. Both locations used very similar equipment and performed the analyses of the samples daily. These two locations had continuous 24-hour air sampling throughout the duration of the event. A mean ratio was then calculated by taking the ratio of each radionuclide to Cs-137 for both locations over the 60 days of interest.

If activity concentration data were available for some days at a site but were missing for other days, estimated values were obtained by either linearly interpolating between known values or by forward or backward correcting for radioactive decay from known measurements. Estimated data were differentiated from measured data in the calculation spreadsheets by color coding. Also, formulas were left in the cells whenever possible so that a reviewer could trace the calculations to determine how a value was obtained.

Values for the dose per activity of intake by inhalation term in Equation C-5 were obtained from ICRP databases of DCs as discussed in Section 3.6 of this report. The ICRP DCs are sex-averaged values and are given for the six age categories used in the dose calculations. The DCs for methyl iodide and elemental iodine were used for gaseous radioiodines.

DCs used in Equation C-5, were multiplied by a factor of three for the doses calculated in this report. The DARWG took this action based on a preliminary probabilistic dose analysis, which indicated that internal doses were not greater than the 95$^{th}$ percentile values determined in the probabilistic analysis. An evaluation of the factors used in the PEP dose calculation indicated that the uncertainties in the dose conversion factors were not conservatively estimated. Upon completing a research of the literature (Kocher et al., 2009 and NCRP, 2009b), DARWG determined that the uncertainties in the DCs could be accounted for by applying a multiplying factor of three to the DCs for inhalation and ingestion for all radionuclides of iodine, cesium and tellurium, which would produce PEP doses that were greater than the 95$^{th}$ percentile values determined in the probabilistic dose analysis. DCs for other radionuclides identified in air at some locations were not adjusted because those radionuclides contributed insignificant amounts to dose.

## C-5. Committed Effective Dose Rate from Water Ingestion

The committed effective dose rate calculation from water ingestion is shown by Equation C-10, with explanation of each term in the paragraphs below the equation.

$$\dot{E(\tau)}_W = \dot{I}_W \times \sum_{i=1}^{3} \left( WA_i \times DC_{Eff,Inh_i} \right) \times 3.7 \tag{C-10}$$

where:

| | | |
|---|---|---|
| $\dot{E(\tau)}_W$ | = | committed effective dose rate from water ingestion (rem $h^{-1}$) |
| $\dot{I}_W$ | = | water ingestion rate (L $h^{-1}$) |
| $WA_i$ | = | measured activity per water volume for species *i* (pCi $L^{-1}$) |
| $DC_{Eff,Inh_i}$ | = | ingestion effective dose coefficient for species *i* (Sv $Bq^{-1}$) |
| 3.7 | = | units conversion (Bq $pCi^{-1}$ rem $Sv^{-1}$) |

In Equation C-10, values for $\dot{I}_W$ for each PEP are derived from values shown in Section 3 of this report. The daily value was divided by 24 hours to facilitate hourly calculations performed in the spreadsheet. It was assumed that every person at a location drank all the water with measured contamination and no credit was given for a person who drank bottled water, other non-contaminated liquids, or from deep well sources of water that were assumed to be free of contamination.

In Equation C-10, the values for $WA_i$ were obtained from analytical laboratories.

In Equation C-10 values for $DC_{Eff,Inh_i}$ were obtained from ICRP databases of DCs as discussed in Section 3.6 of this report. The ICRP DCs are sex averaged values for males and females and are given for the six age categories used in the dose calculations.

The $DC_{Eff,Inh_i}$ values used in Equation C-10, were multiplied by a factor of three for the doses calculated in this report as discussed in the last paragraph of Section C-4 above.

## C-6. Committed Effective Dose Rate from Soil Ingestion

The committed effective dose rate calculation from soil ingestion is shown by Equation C-11. Explanations of each term follow in the paragraphs below the equation.

$$\dot{E(\tau)}_S = \dot{M}_S \times \sum_{i=1}^{5} \left( SA_i \times DC_{Eff,Ing_i} \right) \times 3.7 \tag{C-11}$$

where:

| | | |
|---|---|---|
| $\dot{E(\tau)}_S$ | = | committed effective dose rate from soil ingestion (rem $h^{-1}$) |
| $\dot{M}_S$ | = | soil ingestion rate (g $h^{-1}$) |
| $SA_i$ | = | measured activity per soil mass for species *i* (pCi $g^{-1}$) |
| $DC_{Eff,Ing_i}$ | = | ingestion effective dose coefficient for species *i* (Sv $Bq^{-1}$) |
| 3.7 | = | units conversion (Bq $pCi^{-1}$ rem $Sv^{-1}$) |

In Equation C-11, values for $\dot{M}_S$ for each PEP are derived from values shown in Section 3 of this report. The daily value was divided by 24 hours to facilitate hourly calculations performed in the spreadsheet.

In Equation C-11, values for $SA_i$ were obtained from analytical laboratories.

In Equation C-11 values for the $DC_{Eff,Ing_i}$ were obtained from ICRP databases of DCs as discussed in Section 3.6 of this report. The ICRP DCs are sex-averaged values for male and female and are given for the six age categories used in the dose calculations.

The $DC_{Eff,Ing_i}$ values used in Equation C-11, were multiplied by a factor of three for the doses calculated in this report as discussed in the last paragraph of Section C-4.

## C-7. Whole Body Committed Effective Dose to Effective Dose Ratios

For a particular location, there may not have been available environmental measurements to perform dose calculations for the whole body committed effective dose for air inhalation, water ingestion, or soil ingestion. However, at all locations, external radiation exposure measurements were available for the calculation of the whole body effective dose. This made it possible to use the concept of a dose ratio to calculate the missing committed effective dose term. PEP category-specific whole body committed effective dose to effective dose ratios were calculated at all locations where data were available and maximum values of these ratios were then used to calculate the missing committed effective dose at another location as shown by Equations C-12 through C-14.

$$E(\tau)_{Inh}^{J} = E_{\gamma}^{J} \times \left( \frac{E(\tau)_{Inh}^{K}}{E_{\gamma}^{K}} \right)_{Max} \tag{C-12}$$

where:

| | | |
|---|---|---|
| $E(\tau)_{Inh}^{J}$ | = | committed effective dose at location *J* from air inhalation (rem) |
| $E_{\gamma}^{J}$ | = | effective dose at location *J* from external radiation (rem) |
| $E(\tau)_{Inh}^{K}$ | = | committed effective dose at location *K* from inhalation (rem) |
| $E_{\gamma}^{K}$ | = | effective dose at location *K* from external radiation (rem) |
| *Max* | = | indicates maximum ratio should be used |

$$E(\tau)_W^J = E_\gamma^J \times \left(\frac{E(\tau)_W^K}{E_\gamma^K}\right)_{Max} \tag{C-13}$$

where:

| | | |
|---|---|---|
| $E(\tau)_W^J$ | = | committed effective dose at location *J* from water ingestion (rem) |
| $E_\gamma^J$ | = | effective dose at location *J* from external radiation (rem) |
| $E(\tau)_W^K$ | = | committed effective dose at location *K* from water ingestion (rem) |
| $E_\gamma^K$ | = | effective dose at location *K* from external radiation (rem) |
| *Max* | = | indicates maximum ratio should be used |

$$E(\tau)_S^J = E_\gamma^J \times \left(\frac{E(\tau)_S^K}{E_\gamma^K}\right)_{Max} \tag{C-14}$$

where:

| | | |
|---|---|---|
| $E(\tau)_S^J$ | = | committed effective dose at location *J* from soil ingestion (rem) |
| $E_\gamma^J$ | = | effective dose at location *J* from external radiation (rem) |
| $E(\tau)_S^K$ | = | committed effective dose at location *K* from soil ingestion (rem) |
| $E_\gamma^K$ | = | effective dose at location *K* from external radiation (rem) |
| *Max* | = | indicates maximum ratio should be used |

Maximum ratios of whole body committed effective dose to effective dose were used as a conservative means in calculating the doses. Table 25 of Section 2 shows the locations where environmental data were available. Air concentrations were available at eight DARWG locations; water concentrations at seven DARWG locations; and soil concentrations at five DARWG locations. However, air concentrations from only seven DARWG locations were used in calculations because the data at Misawa AB were close to background and would have contributed very little to dose but resulted in reduced uncertainty.

The committed doses calculated in Equations C-12 through C-14 were multiplied by a factor of three for the doses calculated in this report as discussed in Section C-4 above. It is important to note that in Equations C-5, C-10, and C-11 the DCs were multiplied by a factor of three. However, for Equations C-12 through C-14 doses are calculated in two steps. First, the doses are calculated using no multiplication factors on the DCs; and second the results of the first calculation are multiplied by the factor of three. The reason for this is that Equations C-12 through C-14 contain ratios of doses (and therefore also ratios of DCs) and application of a multiplication factor to the DCs would merely result in the cancellation of the factor since it would appear in the numerator and the denominator of the equations.

The values of the calculated maximum ratios of whole body committed effective dose to effective dose for all 97 PEP categories sorted according to age, physical activity level, and time spent indoors are shown in Table C-7.

Calculating these ratios requires running the data for all the sites having air, water, and soil data. Once the maximum ratios have been determined then the doses for sites with missing data were calculated using the maximum ratios.

Table C-7. Whole body committed effective dose to effective dose for PEP categories

| Age Category | Activity Category | Indoor Category | $E(\tau)_{Air}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Water}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Soil}$ / $E_{Ext\ Rad}$ | CV (N=5) |
|---|---|---|---|---|---|---|---|---|
| 0 to 1 y | High Activity | None | 1.302 | 43% | 0.435 | 61% | 0.032 | 67% |
| 0 to 1 y | High Activity | Lower | 1.542 | 44% | 0.544 | 61% | 0.040 | 67% |
| 0 to 1 y | High Activity | Mean | 1.897 | 44% | 0.707 | 61% | 0.052 | 67% |
| 0 to 1 y | High Activity | Upper | 2.254 | 44% | 0.870 | 61% | 0.064 | 67% |
| 0 to 1 y | Medium Activity | None | 0.672 | 43% | 0.308 | 61% | 0.006 | 67% |
| 0 to 1 y | Medium Activity | Lower | 0.796 | 44% | 0.386 | 61% | 0.008 | 67% |
| 0 to 1 y | Medium Activity | Mean | 0.980 | 44% | 0.501 | 61% | 0.010 | 67% |
| 0 to 1 y | Medium Activity | Upper | 1.164 | 44% | 0.617 | 61% | 0.013 | 67% |
| 0 to 1 y | Low Activity | None | 0.597 | 43% | 0.222 | 61% | 0.002 | 67% |
| 0 to 1 y | Low Activity | Lower | 0.707 | 44% | 0.278 | 61% | 0.002 | 67% |
| 0 to 1 y | Low Activity | Mean | 0.870 | 44% | 0.360 | 61% | 0.003 | 67% |
| 0 to 1 y | Low Activity | Upper | 1.034 | 44% | 0.444 | 61% | 0.004 | 67% |
| 0 to 1 y | Inactive | None | 0.522 | 43% | 0.139 | 61% | 0.001 | 67% |
| 0 to 1 y | Inactive | Lower | 0.618 | 44% | 0.174 | 61% | 0.001 | 67% |
| 0 to 1 y | Inactive | Mean | 0.761 | 44% | 0.226 | 61% | 0.001 | 67% |
| 0 to 1 y | Inactive | Upper | 0.904 | 44% | 0.278 | 61% | 0.001 | 67% |
| >1 y to 2 y | High Activity | None | 1.756 | 44% | 0.319 | 60% | 0.031 | 67% |
| >1 y to 2 y | High Activity | Lower | 2.088 | 44% | 0.399 | 60% | 0.038 | 67% |
| >1 y to 2 y | High Activity | Mean | 2.530 | 44% | 0.506 | 60% | 0.049 | 67% |
| >1 y to 2 y | High Activity | Upper | 3.075 | 45% | 0.637 | 60% | 0.061 | 67% |
| >1 y to 2 y | Medium Activity | None | 0.783 | 44% | 0.172 | 60% | 0.006 | 67% |
| >1 y to 2 y | Medium Activity | Lower | 0.931 | 44% | 0.216 | 60% | 0.008 | 67% |
| >1 y to 2 y | Medium Activity | Mean | 1.129 | 44% | 0.273 | 60% | 0.010 | 67% |

Table C-7. Whole body committed effective dose to effective dose for PEP categories (cont.)

| Age Category | Activity Category | Indoor Category | $E(\tau)_{Air}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Water}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Soil}$ / $E_{Ext\ Rad}$ | CV (N=5) |
|---|---|---|---|---|---|---|---|---|
| >1 y to 2 y | Medium Activity | Upper | 1.372 | 45% | 0.344 | 60% | 0.012 | 67% |
| >1 y to 2 y | Low Activity | None | 0.702 | 44% | 0.105 | 60% | 0.003 | 67% |
| >1 y to 2 y | Low Activity | Lower | 0.835 | 44% | 0.132 | 60% | 0.004 | 67% |
| >1 y to 2 y | Low Activity | Mean | 1.012 | 44% | 0.167 | 60% | 0.005 | 67% |
| >1 y to 2 y | Low Activity | Upper | 1.230 | 45% | 0.210 | 60% | 0.006 | 67% |
| >1 y to 2 y | Inactive | None | 0.622 | 44% | 0.057 | 60% | 0.001 | 67% |
| >1 y to 2 y | Inactive | Lower | 0.739 | 44% | 0.071 | 60% | 0.001 | 67% |
| >1 y to 2 y | Inactive | Mean | 0.895 | 44% | 0.090 | 60% | 0.001 | 67% |
| >1 y to 2 y | Inactive | Upper | 1.088 | 45% | 0.114 | 60% | 0.001 | 67% |
| >2 y to 7 y | High Activity | None | 1.045 | 44% | 0.201 | 60% | 0.017 | 67% |
| >2 y to 7 y | High Activity | Lower | 1.224 | 44% | 0.245 | 60% | 0.021 | 67% |
| >2 y to 7 y | High Activity | Mean | 1.446 | 44% | 0.300 | 60% | 0.026 | 67% |
| >2 y to 7 y | High Activity | Upper | 1.705 | 44% | 0.365 | 60% | 0.031 | 67% |
| >2 y to 7 y | Medium Activity | None | 0.773 | 44% | 0.137 | 60% | 0.003 | 67% |
| >2 y to 7 y | Medium Activity | Lower | 0.905 | 44% | 0.167 | 60% | 0.004 | 67% |
| >2 y to 7 y | Medium Activity | Mean | 1.070 | 44% | 0.205 | 60% | 0.005 | 67% |
| >2 y to 7 y | Medium Activity | Upper | 1.261 | 44% | 0.249 | 60% | 0.006 | 67% |
| >2 y to 7 y | Low Activity | None | 0.654 | 44% | 0.089 | 60% | 0.002 | 67% |
| >2 y to 7 y | Low Activity | Lower | 0.766 | 44% | 0.108 | 60% | 0.002 | 67% |
| >2 y to 7 y | Low Activity | Mean | 0.905 | 44% | 0.133 | 60% | 0.003 | 67% |
| >2 y to 7 y | Low Activity | Upper | 1.067 | 44% | 0.161 | 60% | 0.003 | 67% |
| >2 y to 7 y | Inactive | None | 0.591 | 44% | 0.051 | 60% | 0.000 | 67% |
| >2 y to 7 y | Inactive | Lower | 0.693 | 44% | 0.062 | 60% | 0.000 | 67% |

Table C-7. Whole body committed effective dose to effective dose for PEP categories (cont.)

| Age Category | Activity Category | Indoor Category | $E(\tau)_{Air}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Water}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Soil}$ / $E_{Ext\ Rad}$ | CV (N=5) |
|---|---|---|---|---|---|---|---|---|
| >2 y to 7 y | Inactive | Mean | 0.818 | 44% | 0.077 | 60% | 0.000 | 67% |
| >2 y to 7 y | Inactive | Upper | 0.965 | 44% | 0.093 | 60% | 0.001 | 67% |
| >7 y to 12 y | High Activity | None | 0.635 | 42% | 0.150 | 61% | 0.009 | 68% |
| >7 y to 12 y | High Activity | Lower | 0.727 | 42% | 0.178 | 61% | 0.011 | 68% |
| >7 y to 12 y | High Activity | Mean | 0.852 | 42% | 0.217 | 61% | 0.014 | 68% |
| >7 y to 12 y | High Activity | Upper | 1.019 | 43% | 0.269 | 61% | 0.017 | 68% |
| >7 y to 12 y | Medium Activity | None | 0.457 | 42% | 0.086 | 61% | 0.002 | 68% |
| >7 y to 12 y | Medium Activity | Lower | 0.523 | 42% | 0.103 | 61% | 0.002 | 68% |
| >7 y to 12 y | Medium Activity | Mean | 0.613 | 42% | 0.125 | 61% | 0.003 | 68% |
| >7 y to 12 y | Medium Activity | Upper | 0.733 | 43% | 0.155 | 61% | 0.003 | 68% |
| >7 y to 12 y | Low Activity | None | 0.405 | 42% | 0.054 | 61% | 0.001 | 68% |
| >7 y to 12 y | Low Activity | Lower | 0.463 | 42% | 0.064 | 61% | 0.001 | 68% |
| >7 y to 12 y | Low Activity | Mean | 0.544 | 42% | 0.079 | 61% | 0.001 | 68% |
| >7 y to 12 y | Low Activity | Upper | 0.650 | 43% | 0.097 | 61% | 0.002 | 68% |
| >7 y to 12 y | Inactive | None | 0.354 | 42% | 0.033 | 61% | 0.000 | 68% |
| >7 y to 12 y | Inactive | Lower | 0.405 | 42% | 0.039 | 61% | 0.000 | 68% |
| >7 y to 12 y | Inactive | Mean | 0.475 | 42% | 0.048 | 61% | 0.000 | 68% |
| >7 y to 12 y | Inactive | Upper | 0.568 | 43% | 0.060 | 61% | 0.000 | 68% |
| >12 y to 17 y | High Activity | None | 0.541 | 39% | 0.207 | 63% | 0.007 | 68% |
| >12 y to 17 y | High Activity | Lower | 0.611 | 40% | 0.241 | 63% | 0.008 | 68% |
| >12 y to 17 y | High Activity | Mean | 0.726 | 40% | 0.299 | 63% | 0.010 | 68% |
| >12 y to 17 y | High Activity | Upper | 0.889 | 41% | 0.380 | 63% | 0.013 | 68% |
| >12 y to 17 y | Medium Activity | None | 0.487 | 39% | 0.082 | 63% | 0.001 | 68% |

Table C-7. Whole body committed effective dose to effective dose for PEP categories (cont.)

| Age Category | Activity Category | Indoor Category | $E(\tau)_{Air}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Water}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Soil}$ / $E_{Ext\ Rad}$ | CV (N=5) |
|---|---|---|---|---|---|---|---|---|
| >12 y to 17 y | Medium Activity | Lower | 0.550 | 40% | 0.095 | 63% | 0.002 | 68% |
| >12 y to 17 y | Medium Activity | Mean | 0.653 | 40% | 0.118 | 63% | 0.002 | 68% |
| >12 y to 17 y | Medium Activity | Upper | 0.800 | 41% | 0.150 | 63% | 0.003 | 68% |
| >12 y to 17 y | Low Activity | None | 0.426 | 39% | 0.049 | 63% | 0.001 | 68% |
| >12 y to 17 y | Low Activity | Lower | 0.481 | 40% | 0.057 | 63% | 0.001 | 68% |
| >12 y to 17 y | Low Activity | Mean | 0.571 | 40% | 0.071 | 63% | 0.001 | 68% |
| >12 y to 17 y | Low Activity | Upper | 0.700 | 41% | 0.090 | 63% | 0.001 | 68% |
| >12 y to 17 y | Inactive | None | 0.365 | 39% | 0.030 | 63% | 0.000 | 68% |
| >12 y to 17 y | Inactive | Lower | 0.412 | 40% | 0.035 | 63% | 0.000 | 68% |
| >12 y to 17 y | Inactive | Mean | 0.489 | 40% | 0.043 | 63% | 0.000 | 68% |
| >12 y to 17 y | Inactive | Upper | 0.599 | 41% | 0.055 | 63% | 0.000 | 68% |
| ≥17 y | High Activity | None | 0.484 | 36% | 0.201 | 65% | 0.001 | 69% |
| ≥17 y | High Activity | Lower | 0.530 | 37% | 0.228 | 65% | 0.001 | 69% |
| ≥17 y | High Activity | Mean | 0.628 | 38% | 0.283 | 65% | 0.001 | 69% |
| ≥17 y | High Activity | Upper | 0.771 | 39% | 0.364 | 65% | 0.002 | 69% |
| ≥17 y | Medium Activity | None | 0.313 | 36% | 0.095 | 65% | 0.001 | 69% |
| ≥17 y | Medium Activity | Lower | 0.342 | 37% | 0.107 | 65% | 0.001 | 69% |
| ≥17 y | Medium Activity | Mean | 0.406 | 38% | 0.133 | 65% | 0.001 | 69% |
| ≥17 y | Medium Activity | Upper | 0.498 | 39% | 0.171 | 65% | 0.002 | 69% |
| ≥17 y | Low Activity | None | 0.251 | 36% | 0.068 | 65% | 0.000 | 69% |
| ≥17 y | Low Activity | Lower | 0.275 | 37% | 0.077 | 65% | 0.001 | 69% |
| ≥17 y | Low Activity | Mean | 0.327 | 38% | 0.095 | 65% | 0.001 | 69% |
| ≥17 y | Low Activity | Upper | 0.401 | 39% | 0.123 | 65% | 0.001 | 69% |
| ≥17 y | Inactive | None | 0.251 | 36% | 0.047 | 65% | 0.000 | 69% |

**Table C-7. Whole body committed effective dose to effective dose for PEP categories (cont.)**

| Age Category | Activity Category | Indoor Category | $E(\tau)_{Air}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Water}$ / $E_{Ext\ Rad}$ | CV (N=7) | $E(\tau)_{Soil}$ / $E_{Ext\ Rad}$ | CV (N=5) |
|---|---|---|---|---|---|---|---|---|
| ≥17 y | Inactive | Lower | 0.275 | 37% | 0.053 | 65% | 0.000 | 69% |
| ≥17 y | Inactive | Mean | 0.327 | 38% | 0.067 | 65% | 0.000 | 69% |
| ≥17 y | Inactive | Upper | 0.401 | 39% | 0.086 | 65% | 0.000 | 69% |
| Humanitarian Relief | Extreme Activity | None | 0.516 | 34% | 0.302 | 61% | 0.002 | 63% |

### C-8. Total Thyroid Dose

Equations C-15 and C-16 summarize the thyroid total equivalent dose calculation.

$$\dot{H}_T = \dot{X}_{T,\gamma} \times Q \ + \ H\dot{(\tau)}_{T,Inh} + H\dot{(\tau)}_{T,W} + H\dot{(\tau)}_{T,S} \qquad \text{(C-15)}$$

where:

| | | |
|---|---|---|
| $\dot{H}_T$ | = | total thyroid dose rate (rem $h^{-1}$) |
| $\dot{X}_{T,\gamma}$ | = | external dose rate (R $h^{-1}$) |
| $Q$ | = | dose per exposure conversion factor (rem $R^{-1}$) |
| $H\dot{(\tau)}_{T,Inh}$ | = | thyroid committed equivalent dose rate from inhalation (rem $h^{-1}$) |
| $H\dot{(\tau)}_{T,W}$ | = | thyroid committed equivalent dose rate from water ingestion (rem $h^{-1}$) |
| $H\dot{(\tau)}_{T,S}$ | = | thyroid committed equivalent dose rate from soil ingestion (rem $h^{-1}$) |

$$H_T = \sum_{j=1}^{1440} \dot{H}_{T_j} \qquad \text{(C-16)}$$

where:

| | | |
|---|---|---|
| $H_T$ | = | total thyroid dose over all hours in the 60-day period (rem) |
| $\dot{H}_{T_j}$ | = | total thyroid dose rate for hour *j* (rem $h^{-1}$) |

### C-9. Thyroid Dose Rate from External Radiation

The thyroid dose rate is calculated by Equation C-3 and assumes that the entire body is irradiated so that the dose to the thyroid from external radiation is the same as the whole body dose. The IDRFE also applies to thyroid external dose calculations as discussed in Section C-3 of this appendix.

### C-10. Thyroid Committed Equivalent Dose Rate from Air Inhalation

The thyroid committed equivalent dose rate from air inhalation is calculated using the same form as Equation C-5 with slightly different symbols to represent equivalent dose rather than effective dose. Also, the dose per activity intake from inhalation term is for the thyroid dose but it is still obtained from ICRP databases of DCs as discussed in Section 3.6 of this report. As previously discussed, the ICRP DCs are sex-averaged values and are given for the six age categories used in the dose calculations. For DCs for iodine vapors, the values for methyl iodide were used as a closest match to those available in the literature. As before, the thyroid equivalent DCs were multiplied by a factor of three for the doses calculated in this report as discussed in the last paragraph of Section C-4 above.

## C-11. Thyroid Committed Equivalent Dose Rate from Water Ingestion

The thyroid committed equivalent dose rate from water ingestion is calculated using the same form as Equation C-10 with slightly different symbols to represent equivalent dose rather than effective dose. Also, the dose per activity intake from inhalation term is for the thyroid dose but it is still obtained from ICRP databases of DCs as discussed in Section 3.6 of the report. As before, the thyroid equivalent DCs were multiplied by a factor of three for the doses calculated in this report as discussed in the last paragraph of Section C-4 above.

## C-12. Thyroid Committed Equivalent Dose Rate from Soil Ingestion

The thyroid committed equivalent dose rate calculation from soil ingestion takes the same form as equation C-11 with slightly different symbols to represent equivalent dose versus effective doses. Also, the dose per activity intake from inhalation term is for the thyroid dose but it is still obtained from ICRP databases of DCs as discussed in Section 3.6 of this report. As before, the thyroid equivalent DCs were multiplied by a factor of three for the doses calculated in this report as discussed in the last paragraph of Section C-4 above.

## C-13. Weighted Dose Coefficients of Thyroid Committed Equivalent Dose

There was a need for a method to calculate thyroid committed equivalent doses from air inhalation ($H(\tau)_{T,inh}$), water ingestion ($H(\tau)_{T,W}$), and soil ingestion ($H(\tau)_{T,S}$), for those locations where there may not have been air, water or soil environmental measurements available. To handle these situations the DARWG used weighted ratios of DCs. The weighting factors used were calculated without the use of IDRFI to keep the ratio independent of the time indoors in order to produce the corrected modeled response in the overall calculation of the thyroid committed equivalent dose as a function of time indoors, i.e., $H(\tau)_{T,inh}$ should decrease with increasing time indoors and $H(\tau)_{T,W}$ and $H(\tau)_{T,S}$ should not be a function of time indoors since IDRFI only applies to inhalation.

For cases when water or soil measurements were missing at a location but air measurements were available then the $H(\tau)_{T,W}$ and $H(\tau)_{T,S}$ thyroid values were calculated using Equations C-17 and C-18.

$$H(\tau)_{T,W}^{J} = E(\tau)_{W}^{J} \times \sum_{i=1}^{22} \left[ \frac{DC_{T,Inh_i}}{DC_{Eff,Inh_i}} \times \left( \frac{H(\tau)_{T,Inh_i}}{H(\tau)_{T,Inh}} \right)_J \right] \tag{C-17}$$

where:

| | | |
|---|---|---|
| $H(\tau)_{T,W}^{J}$ | = | thyroid committed equivalent dose at location $J$ from water ingestion (rem) |
| $E(\tau)_{W}^{J}$ | = | committed effective dose at location $J$ from water ingestion (rem) |
| $DC_{T,Inh_i}$ | = | thyroid equivalent dose coefficient for inhalation for species $i$ (Sv $Bq^{-1}$) |
| $DC_{Eff,Inh_i}$ | = | effective dose coefficient for inhalation for species $i$ (Sv $Bq^{-1}$) |
| $H(\tau)_{T,Inh_i}$ | = | thyroid committed equivalent dose from inhalation for species $i$ (rem) |

$H(\tau)_{T,Inh}$ = total thyroid committed equivalent dose from inhalation (rem)

$$H(\tau)_{T,S}^{J} = E(\tau)_{S}^{J} \times \sum_{i=1}^{22} \left[ \frac{DC_{T,Inh_i}}{DC_{Eff,Inh_i}} \times \left( \frac{H(\tau)_{T,Inh_i}}{H(\tau)_{T,Inh}} \right)_J \right] \quad \text{(C-18)}$$

where:

$H(\tau)_{T,S}^{J}$ = thyroid committed equivalent dose at location *J* from soil ingestion (rem)
$E(\tau)_{S}^{J}$ = committed effective dose at location *J* from soil ingestion (rem)
(remaining variables are defined above)

For cases when air concentration measurements were missing at a location then the $H(\tau)_{T,inh}$, $H(\tau)_{T,W}$, or ($H(\tau)_{T,S}$ were calculated using Equations C-19 through C-21. All variables are defined following Equation C-21 or with previous equations.

$$H(\tau)_{T,Inh}^{J} = E(\tau)_{Inh}^{J} \times \sum_{i=1}^{22} \left[ \frac{DC_{T,Inh_i}}{DC_{Eff,Inh_i}} \times \left( \frac{H(\tau)_{T,Inh_i}}{H(\tau)_{T,Inh}} \right)_K \right]_{max} \quad \text{(C-19)}$$

$$H(\tau)_{T,W}^{J} = E(\tau)_{W}^{J} \times \sum_{i=1}^{22} \left[ \frac{DC_{T,Ing_i}}{DC_{Eff,Ing_i}} \times \left( \frac{H(\tau)_{T,W_i}}{H(\tau)_{T,W}} \right)_K \right]_{max} \quad \text{(C-20)}$$

$$H(\tau)_{T,S}^{J} = E(\tau)_{S}^{J} \times \sum_{i=1}^{22} \left[ \frac{DC_{T,Ing_i}}{DC_{Eff,Ing_i}} \times \left( \frac{H(\tau)_{T,S_i}}{H(\tau)_{T,S}} \right)_K \right]_{max} \quad \text{(C-21)}$$

where:

$H(\tau)_{T,Inh}^{J}$ = thyroid committed equivalent dose at location *J* from inhalation (rem)
$H(\tau)_{T,W}^{J}$ = thyroid committed equivalent dose at location *J* from water ingestion (rem)
$H(\tau)_{T,S}^{J}$ = thyroid committed equivalent dose at location *J* from soil ingestion (rem)
$DC_{T,Ing_i}$ = thyroid equivalent dose coefficient for ingestion for species *i* (Sv $Bq^{-1}$)
$DC_{Eff,Ing_i}$ = effective dose coefficient for ingestion for species *i* (Sv $Bq^{-1}$)
$max$ = maximum value from all sites with data

The thyroid committed doses calculated in Equations C-17 through C-21 were multiplied by a factor of three for the doses calculated in this report for reasons discussed in Section C-4 above.

The weighted ratios discussed in this section are functions of age and location but not of activity categories or time spent indoors categories. The maximum weighted ratios for air, water, and soil were calculated to be 20, 21, and 21, respectively. These ratios are driven by the predominate fraction of iodine concentration in the measurements, which heavily weight the thyroid dose to the whole body effective dose conversion factors.

The values of the weighted ratios inside the summation terms of Equations C-17 through C-19 are shown by the yellow and pink shaded cells in Table C-8. Equations C-22 through C-24 were used to calculate the ratios inside the summation terms in Equations C-17 through C-19 at locations where environmental data existed for air, water, or soil respectively. These calculated ratio values are shown in the non-shaded cells in Table C-8. Blue shaded cells in Table C-8 contain ratios for locations where radioactive material concentrations were measured but whose values were less than MDA.

$$R_{Inh}^{K} = \sum_{i=1}^{22} \left[ \frac{DC_{T,Inh_i}}{DC_{Eff,Inh_i}} \times \left( \frac{H(\tau)_{T,Inh_i}}{H(\tau)_{T,Inh}} \right)_K \right] \tag{C-22}$$

where:

$R_{Inh}^{K}$ = The sum, over all species *i*, of the ratio of thyroid to effective dose coefficients for inhalation, weighted by the ratio of species *i* thyroid dose to total thyroid dose for inhalation at location *K* (no units)

$$R_{W}^{K} = \sum_{i=1}^{22} \left[ \frac{DC_{T,Ing_i}}{DC_{Eff,Ing_i}} \times \left( \frac{H(\tau)_{T,W_i}}{H(\tau)_{T,W}} \right)_K \right] \tag{C-23}$$

where:

$R_{W}^{K}$ = The sum, over all species *i*, of the ratio of thyroid to effective dose coefficients for ingestion, weighted by the ratio of species *i* thyroid dose to total thyroid dose for water ingestion at location *K*] (no units)

$$R_{S}^{K} = \sum_{i=1}^{22} \left[ \frac{DC_{T,Ing_i}}{DC_{Eff,Ing_i}} \times \left( \frac{H(\tau)_{T,S_i}}{H(\tau)_{T,S}} \right)_K \right] \tag{C-24}$$

where:

$R_{S}^{K}$ = The sum, over all species *i*, of the ratio of thyroid to effective dose coefficients for ingestion, weighted by the ratio of species *i* thyroid dose to total thyroid dose for soil ingestion at location *K* (no units)

**Table C-8. Weighted ratios of DCs used to calculate thyroid committed equivalent dose**

| Location | Age Category | Air Inhalation Ratio | Water Ingestion Ratio | Soil Ingestion Ratio |
|---|---|---|---|---|
| D-00 Ref Site IMS | 0.3 | 18.663 | 20.032 | 18.663 |
| | 1 | 18.448 | 19.694 | 18.448 |
| | 5 | 19.352 | 20.536 | 19.352 |
| | 10 | 18.735 | 18.388 | 18.735 |
| | 15 | 18.465 | 18.295 | 18.465 |
| | 20 | 18.298 | 17.089 | 18.298 |
| | 20 H | 18.298 | 17.089 | 18.298 |
| D-01 Misawa AB | 0.3 | 13.461 | <MDA | 13.461 |
| | 1 | 14.327 | <MDA | 14.327 |
| | 5 | 15.324 | <MDA | 15.324 |
| | 10 | 13.886 | <MDA | 13.886 |
| | 15 | 13.146 | <MDA | 13.146 |
| | 20 | 11.763 | <MDA | 11.763 |
| | 20 H | 11.763 | <MDA | 11.763 |
| D-02 Sendai Airport | 0.3 | 15.503 | 15.503 | 18.282 |
| | 1 | 15.989 | 15.989 | 18.558 |
| | 5 | 16.880 | 16.880 | 18.949 |
| | 10 | 15.840 | 15.840 | 15.926 |
| | 15 | 15.551 | 15.551 | 14.232 |
| | 20 | 14.703 | 14.703 | 12.099 |
| | 20 H | 14.703 | 14.703 | 12.099 |
| D-03 City of Ishinomaki | 0 | 15.360 | 15.360 | 15.360 |
| | 1 | 15.972 | 15.972 | 15.972 |
| | 5 | 16.310 | 16.310 | 16.310 |
| | 10 | 13.925 | 13.925 | 13.925 |
| | 15 | 11.495 | 11.495 | 11.495 |
| | 20 | 9.428 | 9.428 | 9.428 |
| | 20 H | 9.428 | 9.428 | 9.428 |

Legend: ratio based on measurement (non-shaded); weighted ratios from Eqns. C-15 and C-16 (yellow), or C-18 and C-19 (pink)

D-08 and D-09, and D-10 and D-11 use the same water data from their respective nearest MEXT stations.

D-08 through D-11 use D-08 air concentration data.,

**Table C-8. Weighted ratios of DCs used to calculate thyroid committed equivalent dose (cont.)**

| Location | Age Category | Air Inhalation Ratio | Water Ingestion Ratio | Soil Ingestion Ratio |
|---|---|---|---|---|
| D-04 City of Yamagata | 0.3 | 20.000 | <MDA | 21.000 |
| | 1 | 20.000 | <MDA | 21.000 |
| | 5 | 20.000 | <MDA | 21.000 |
| | 10 | 20.000 | <MDA | 21.000 |
| | 15 | 20.000 | <MDA | 21.000 |
| | 20 | 20.000 | <MDA | 21.000 |
| | 20 H | 20.000 | <MDA | 21.000 |
| D-06 Hyakuri AB | 0.3 | 20.000 | 20.142 | 21.000 |
| | 1 | 20.000 | 19.759 | 21.000 |
| | 5 | 20.000 | 20.634 | 21.000 |
| | 10 | 20.000 | 18.563 | 21.000 |
| | 15 | 20.000 | 18.635 | 21.000 |
| | 20 | 20.000 | 17.561 | 21.000 |
| | 20 H | 20.000 | 17.561 | 21.000 |
| D-07 City of Oyama | 0.3 | 20.000 | 19.451 | 21.000 |
| | 1 | 20.000 | 19.347 | 21.000 |
| | 5 | 20.000 | 20.018 | 21.000 |
| | 10 | 20.000 | 17.494 | 21.000 |
| | 15 | 20.000 | 16.646 | 21.000 |
| | 20 | 20.000 | 14.923 | 21.000 |
| | 20 H | 20.000 | 14.923 | 21.000 |
| D-08 Yokota AB | 0.3 | 18.991 | 20.159 | 18.765 |
| | 1 | 18.623 | 19.769 | 18.692 |
| | 5 | 19.477 | 20.650 | 19.335 |
| | 10 | 18.927 | 18.591 | 16.885 |
| | 15 | 18.731 | 18.691 | 16.127 |
| | 20 | 18.663 | 17.639 | 14.418 |
| | 20 H | 18.663 | 17.639 | 14.418 |

Legend: ratio based on measurement (non-shaded); weighted ratios from Eqns. C-17 and C-18 (yellow), C-19 and C-21 (pink), or C-22 (blue).
D-08 and D-09, and D-10 and D-11 use the same water data from their respective nearest MEXT stations.
D-08 through D-11 use D-08 air concentration data.

**Table C-8. Weighted ratios of DCs used to calculate thyroid committed equivalent dose (cont.)**

| Location | Age Category | Air Inhalation Ratio | Water Ingestion Ratio | Soil Ingestion Ratio |
|---|---|---|---|---|
| D-09 Akasaka Press Center | 0.3 | 18.991 | 20.159 | 19.368 |
| | 1 | 18.623 | 19.769 | 19.145 |
| | 5 | 19.477 | 20.650 | 19.917 |
| | 10 | 18.927 | 18.591 | 17.700 |
| | 15 | 18.731 | 18.691 | 17.429 |
| | 20 | 18.663 | 17.639 | 16.046 |
| | 20 H | 18.663 | 17.639 | 16.046 |
| D-10 Atsugi NAF | 0.3 | 18.991 | 20.556 | 18.944 |
| | 1 | 18.623 | 20.000 | 18.914 |
| | 5 | 19.477 | 21.000 | 19.535 |
| | 10 | 18.927 | 19.231 | 16.979 |
| | 15 | 18.731 | 20.000 | 16.052 |
| | 20 | 18.663 | 19.545 | 14.261 |
| | 20 H | 18.663 | 19.545 | 14.261 |
| D-11 Yokosuka NB | 0.3 | 18.991 | 20.556 | 18.935 |
| | 1 | 18.623 | 20.000 | 18.900 |
| | 5 | 19.477 | 21.000 | 19.524 |
| | 10 | 18.927 | 19.231 | 16.978 |
| | 15 | 18.731 | 20.000 | 16.067 |
| | 20 | 18.663 | 19.545 | 14.285 |
| | 20 H | 18.663 | 19.545 | 14.285 |
| D-12 Camp Fuji | 0.3 | 20.000 | <MDA | 21.000 |
| | 1 | 20.000 | <MDA | 21.000 |
| | 5 | 20.000 | <MDA | 21.000 |
| | 10 | 20.000 | <MDA | 21.000 |
| | 15 | 20.000 | <MDA | 21.000 |
| | 20 | 20.000 | <MDA | 21.000 |
| | 20 H | 20.000 | <MDA | 21.000 |

Legend: ratio based on measurement (non-shaded); weighted ratios from Eqns. C-17 and C-18 (yellow), C-19 and C-21 (pink), or C-22 (blue).
D-08 and D-09, and D-10 and D-11 use the same water data from their respective nearest MEXT stations.
D-08 through D-11 use D-08 air concentration data.

**Table C-8. Weighted ratios of DCs used to calculate thyroid committed equivalent dose (cont.)**

| Location | Age Category | Air Inhalation Ratio | Water Ingestion Ratio | Soil Ingestion Ratio |
|---|---|---|---|---|
| D-13 Iwakuni MCAS | 0.3 | 20.000 | <MDA | 21.000 |
| | 1 | 20.000 | <MDA | 21.000 |
| | 5 | 20.000 | <MDA | 21.000 |
| | 10 | 20.000 | <MDA | 21.000 |
| | 15 | 20.000 | <MDA | 21.000 |
| | 20 | 20.000 | <MDA | 21.000 |
| | 20 H | 20.000 | <MDA | 21.000 |
| D-14 Sasebo NB | 0.3 | 20.000 | <MDA | 21.000 |
| | 1 | 20.000 | <MDA | 21.000 |
| | 5 | 20.000 | <MDA | 21.000 |
| | 10 | 20.000 | <MDA | 21.000 |
| | 15 | 20.000 | <MDA | 21.000 |
| | 20 | 20.000 | <MDA | 21.000 |
| | 20 H | 20.000 | <MDA | 21.000 |

Legend: ratio based on measurement (non-shaded); weighted ratios from Eqns. C-17 and C-18 (yellow), C-19 and C-21 (pink), or C-22 (blue).
D-08 and D-09, and D-10 and D-11 use the same water data from their respective nearest MEXT stations.
D-08 through D-11 use D-08 air concentration data.

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## Appendix D.

## External Monitoring, Internal Monitoring Scans, and Urine Bioassays

This appendix summarizes the external monitoring, internal monitoring (IM) by whole body and thyroid scans, and urine bioassays that were used to monitor people.

### D-1. Introduction

There are two basic sources of radiation exposure to people, external and internal. Radiation that is generated outside the body can give an individual an external dose and radioactive materials that are deposited in the body and undergo radioactive decay while inside the body can give an individual an internal dose.

Dosimeters were used to measure external dose. Some individuals already had dosimeters in their possession because of their normal job function (for example some hospital, shipyard, and shipboard individuals normally wear dosimeters), and others were issued dosimeters because of their operational assignments. For this report, preliminary dosimeter results were compared with calculated values as a validity check, i.e., no individual dosimeter measurement should be greater that the calculated value for external dose, under the assumed circumstances of exposure and radiation environments. Final dosimeter results and the placement (location) of individuals during the OTR period are pending.

IM scans and urine bioassays were performed to determine internal doses.

For this report, preliminary IM results were compared with calculated values as a validity check, i.e., no individual IM measurement should be greater that the calculated value for internal dose. Final IM results and the locations of individuals during the OTR period are pending.

For this report, there were no urine bioassay data available. About 180 urine bioassay samples that were collected are pending analysis and evaluation.

Most people who were issued personal dosimeters also went through IM scans. A number of individuals that did not have dosimeters also went through IM scans to help determine more accurate estimates of total radiation dose for the PEPs. Criteria for dosimeter issue and IM selection of individuals are discussed later in this appendix.

Dosimeters, IM scans, and bioassays are direct measurements of an individual’s dose and therefore are the best measurements to use in the calculation of an individual’s dose.

Use of environmental measurements to calculate an individual’s dose requires knowing where the individual was throughout the exposure period, estimating how long the individual was in a particular environment, and of course having all of the environmental radiological data as a function of time and location. The use of environmental data to estimate external and internal doses requires a greater number of measurements and assumptions to be made and generally results in a greater uncertainty than the direct measurement of dose through dosimetry or IM scans. For this report, environmental measurements were used to estimate a dose for each PEP described in Section 3. At a later date, if a more detailed dose estimate is needed for an individual, direct dosimeter and IM measurements will be considered in the dose reconstruction

process. The future calculation of an individual's dose would be expected to produce a dose that is less than the dose estimated for the PEPs defined in this report.

In the absence of individual and environmental measurements the next best approach for determining an individual's external and internal dose is by the modeling of the sources of radiation and radioactive materials. In this case the source of radiation and radioactive material was the result of releases from the FDNPS. It can be difficult to accurately model environmental releases resulting from damage to reactor cores or fuel storage pools due to the large number of variables that can affect the predicted outcome. In this report, it was not necessary to use reactor core or fuel pool release models because there were sufficient radiological environmental measurements available to calculate estimates for the PEPs defined.

Figure D-1 illustrates the hierarchy of all the different types of data potentially available for use in a dose reconstruction. Preliminary estimates indicate that there were approximately 70,000 people (shore-based, aircrew, and shipboard individuals) who could be included in the POI for dose reconstruction for the OTR. Preliminary figures show that about 4,000 persons (about 6 percent) wore dosimeters during at least part of the 60-day period and about 8,400 (12 percent) had IM that was usually done once between March 12 and August 31, 2011. These measurements are labeled "Best Dose Data" because they are direct measurements of dose with the smallest uncertainty. The "Next Best Data" are environmental measurements that require additional assumptions and calculations for dose reconstruction and will have a larger uncertainty. The "Helpful Data" measurements or results, which may involve modeling, assessment of meteorology, or estimates of reactor core depletion, tend to exhibit higher uncertainty than the other data types and are only used in the absence of the other types of data, or for confirmation of the results obtained with the other types.

## D-2. External Monitoring

The USA, USN, and USAF all have large, well-established, nationally-accredited dosimetry centers in CONUS.

- The USN and USAF provided electronic personal dosimeters (EPDs) that allow for real time, or active, measurements of external dose while they are being worn by the individual.
- The USN and USAF also provided thermoluminescent dosimeters (TLDs). These are passive devices that are read at the end of the monitoring period for each individual.
- The USA provided optically stimulated luminescent (OSL) dosimeters that had the potential to be read in the field but were not because of concerns that the readers would become contaminated in the operational setting. Therefore, OSL dosimeters were used as passive devices and were read at the end of the monitoring period for each individual.

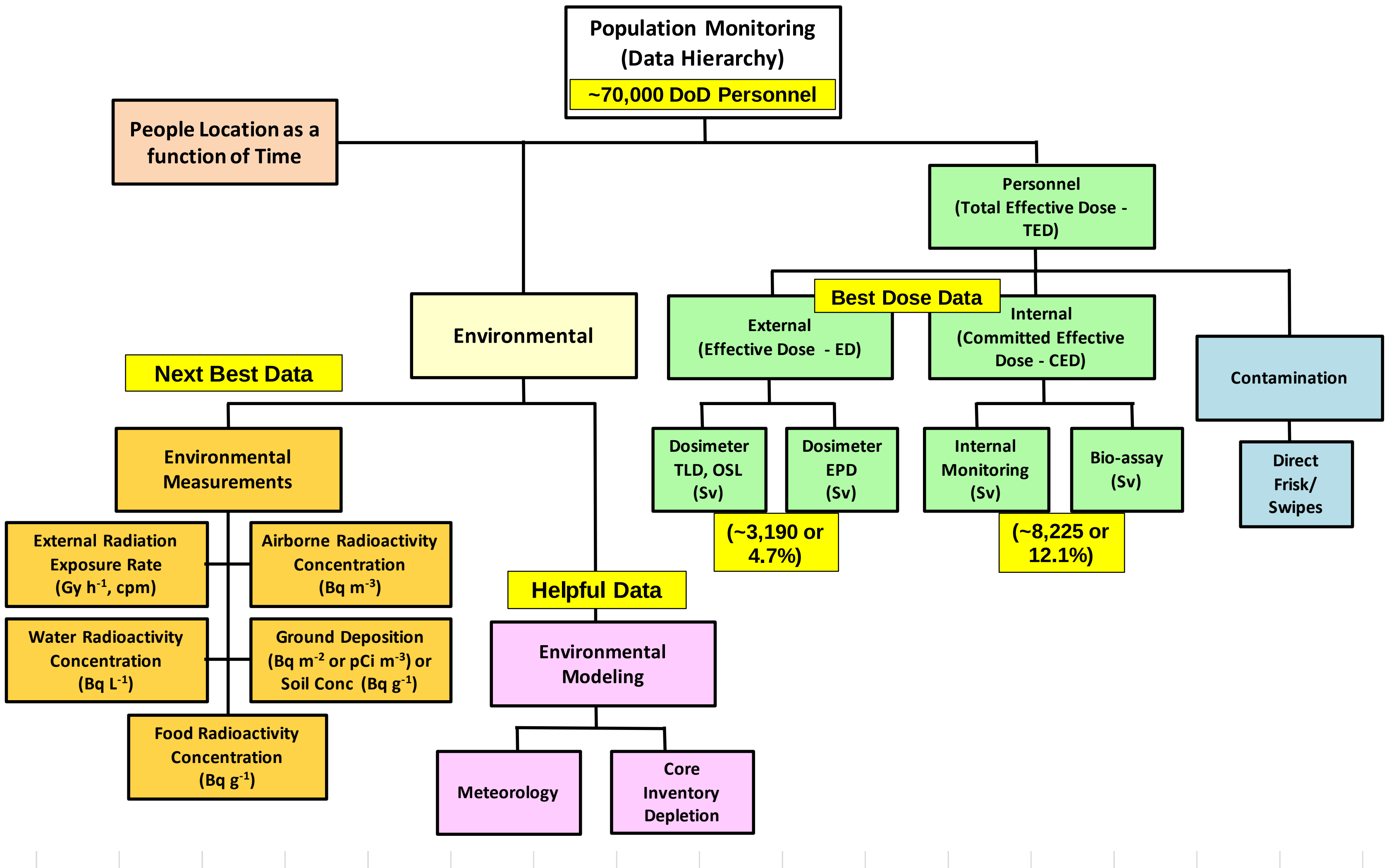


**Figure D-1. Hierarchy of data**

Individual monitoring periods for people issued TLDs and OSL dosimeters could be on the order of days to weeks to months, depending on the circumstances of the individual's duties and locations. Further information on the dosimetry equipment used by each of the services can be found in Appendix A.

The groups of individuals who were specifically issued dosimeters as part of their OT participation were as follows (USPACOM, 2011a).

- Those persons who entered warm and hot zones.
    - Warm Zone: Initially defined as the area between 25 and 125 nautical miles of FDNPS or an area in which general area radiation levels were between 0.1 and 10 mrem $h^{-1}$ (USFJ, 2011a) and later revised to an area between 40 and 80 km from FDNPS or an area in which general area radiation levels were between 0.1 and 10 mrem $h^{-1}$ (USFJ, 2011b).
    - Hot Zone: Initially defined as the area within 25 nautical miles of FDNPS or an area in which general area radiation levels were in excess of 10 mrem $h^{-1}$ (USFJ, 2011a) and later revised to an area within 40 km of FDNPS or an area in which general area radiation levels were in excess of 10 mrem $h^{-1}$ (USFJ, 2011b).
- Persons who could come into contact with loose surface contamination such as those involved with equipment decontamination.
- Persons who were part of an aircrew, which flew through an identified plume.
- Persons who were likely to exceed a TED control level of 0.3 rem as predicted from exposure models and environmental measurements.

Some individuals who already had a dosimeter in their possession as part of their normal job function included the following:

- Nuclear-trained individuals who were at Yokosuka Shipyard or on aircraft carriers.
- Medical individuals who were working around radiation sources.

Each person in the POI may have none, one, or several individual dosimeter measurements during the 60-day OTR period. Also, a single dosimeter issued to an individual could include some dates prior to or after the 60-day OTR period, depending on issue and collection dates. Also, there were cases when an individual was issued more than one dosimeter at a time. These details will need to be considered in the future when dosimeter data are used as part of an individual's dose reconstruction.

The persons who entered the warm or hot zones are not considered as specific PEPs in this assessment. The activities that warranted the wearing of dosimeters could involve doses that are in addition to any PEP dose that might be assigned.

Table D-1 provides a summary of the numbers of dosimeters reported, and Table D-2 provides a summary of reported results.

**Table D-1. Personnel dosimeter use by DOD-affiliated individuals**

| Service | Sent | Type | Number Reported |
|---|---|---|---|
| USA | 2,000 | OSL | 326 |
| USN | 685 | EPD | 126 |
| USN | 14,000 | TLD | 1,669 |
| USAF | 1,400 | EPD | 711 |
| USAF | 6,500 | TLD | 364 |
| Total | 24,585 | | 3,196 |

**Table D-2. External monitoring results**

| Service (Type) | Total Number of Dosimeters | Number of Dosimeters per Dose Range (mrem) | | | | | |
|---|---|---|---|---|---|---|---|
| | | 0 | 1-25 | 26-50 | 51-100 | 101-500 | >501 |
| USA (OSL) | 326 | 77 | 247 | 0 | 1 | 1 | 0 |
| USN (TLD) | 1669 | 1349 | 310 | 7 | 3 | 0 | 0 |
| USN (EPD) | 126 | 16 | 110 | 0 | 0 | 0 | 0 |
| USAF (EPD) | 711 | 90 | 620 | 1 | 0 | 0 | 0 |
| USAF (TLD) | 364 | 361 | 3 | 0 | 0 | 0 | 0 |
| Grand Total | 3196 | 1893 | 1290 | 8 | 4 | 1 | 0 |
| Percent of Total | 100% | 59.2% | 40.4% | 0.3% | 0.1% | 0.0% | 0.0% |

An initial review of external monitoring data shown in Table D-2 indicates that 99.6 percent of the reported doses are 25 mrem (0.25 mSv) or less and are consistent with the calculated estimates of external radiation doses (see Section 5.2.1). Thirteen (13, 0.4 percent of 3,196 reported) dosimeter results are larger than the estimates of external radiation dose for adults. These anomalous results are undergoing investigation to determine the circumstances of the exposure.

The doses reported in Table D-2 are undergoing follow-on review by the DARWG to: (1) differentiate occupational and OT dose, (2) validate background and transit doses, (3) consider wearing periods, locations, duty assignments, and other personal information, and (4) investigate sources of anomalous doses.

## D-3. Internal Monitoring Scans

IM measurements were made to assess whether individuals had an intake of radioactive material released from the FDNPS. The equipment used for IM was of two types, i.e., fixed scanners purposefully designed for IM and portable instruments adapted for IM (both whole body and thyroid).

Portable instruments were used to increase the number of individuals who could be monitored and to bring monitoring to ships and remote locations. The portable instruments were used as screening devices to identify those individuals with the potential for some measurable intake of radioactive material who were then sent for a confirmation by fixed scan, where the internally deposited radionuclides could be positively identified through spectrometric analysis.

Fixed scanners included Canberra ACCUSCAN and FASTSCAN systems. Both of these systems measure the whole body and thyroid regions and provide full spectroscopic identification of nuclides. FASTSCAN systems were established at the Kadena AB on the island of Okinawa Japan, and at the Yokosuka NB. One ACCUSCAN system was established at Atsugi NAF. None of these systems had been set up in Japan prior to the March 11, 2011 earthquake. Existing FASTSCAN systems setup in CONUS at the Puget Sound Naval Shipyard, WA, San Diego NB, CA and at the Intermediate Maintenance Facility in Bremerton, WA were used to monitor about 1,013 individuals prior to the establishment of the fixed scanners in Japan.

The FASTSCAN systems used two 3″ × 5″ × 16″ fixed NaI(Tl) detectors, while the ACCUSCAN system used two germanium moveable detectors. Both systems used several thousand pounds of shielding to lower the influence of background radiation and to provide a lower minimum detectable activity. Figure D-2 illustrates an ACCUSCAN in operation.

Twenty-five (25) multi-purpose survey meters (E-600) with attached SPA-3 (2″ diameter × 2″ thick NaI(Tl) smart probe system) scintillation probes were used for portable systems. The portable systems were used in gross count, open window mode and provided no spectrum or nuclide identification. Portable IM instruments were also used at the locations where fixed IM scanners were located and at other sites as needed including on ships. Figure D-2 illustrates several individuals undergoing IM screening. Further information about the IM equipment used can be found in Appendix A.

**Figure D-2. Individuals undergoing IM screening**

About 8,380 individuals had IM in two phases as follows:

1. Phase 1. Individuals with Higher Potential for Exposure
    a. In CONUS on individuals working in Yokosuka NB between March 11 and April 13, 2011. There were 1,013 individuals internally monitored from March 16 through April 13 (29 Days) using fixed scanners in San Diego, CA, and Bremerton, WA.
    b. In Japan from April 14 through August 31, 2011 for about 7,212 individuals falling in the following categories:
        i. Active duty personnel operating within the Sendai area.
        ii. Aviators, i.e. helicopter pilots and aircrews who flew through known plumes.
        iii. Personnel supporting aviation operations and aircraft/ship decontamination.
        iv. Supporting ship crew, including nuclear trained individuals.
        v. Supporting shore activity personnel.
        vi. Naval Nuclear Propulsion personnel.
        vii. Ten percent selected randomly from other groups.
        viii. Additionally, each service component was asked to provide lists of individuals who had a higher potential for internal exposure who were then internally monitored.
2. Phase 2: Voluntary Open Availability. In Japan from July 26 through August 31, 2011. During this period, IM was voluntary for military, civilian employees, contractors, and beneficiaries; including infants and children. One hundred fifty five (155) people (51 dependent children, 46 dependent adults, 38 DOD civilian employees/contractors, and 20 active duty military) were monitored, and all of these measurements were below the minimum detectable activity (MDA).

IM results for individuals in the two phases are shown in Table D-3.

With regard to the stated doses in Table D-1, there have been numerous assumptions made (such as particle size, inhalation class, concentrations of radioactive nuclides in the air, etc.), and literature values used (such as Dose Coefficients [DCs] from ICRP Report 71 and Intake Retention Factors from ICRP Report 68, etc.). A technical report, DTRA-TR-12-004, *Radiation Internal Monitoring by In Vivo Scanning in Operation Tomodachi,* will be completed by the end of 2012.

The concept of “unmeasured” or “missed” intake activity (or corresponding dose) is important for an appreciation of the stated doses and for implications of “less than MDA” or “greater than MDA.” For a given MDA, the missed intake is the potential unmeasured intake activity that results because of the effective elimination of the radionuclide from the body with time. Thus, a reading at the MDA of the instrument immediately after intake may result in measuring 70 percent of the intake with a missed activity of 30 percent of the intake. However, if the same intake measurement is delayed for one effective half-life, then it is possible that only 35 percent of the intake would be measured and that the missed activity would represent 65 percent of the intake. Thus, for a given MDA, the longer the time that elapses between intake and measurement, the greater the missed intake activity and corresponding dose. This presents the

possibility that the unmeasured dose for those monitored during the "Open Availability Phase" could exceed the doses estimated for persons who were found to contain radionuclides when measured at earlier times.

**Table D-3. Summary of internal monitoring scan results**

| **Phase 1: Higher Potential for Internal Exposure** | |
|---|---|
| Personnel Monitored with <MDA | 8042 (98%) |
| Personnel Monitored with ≥MDA | 183 (2%) |
| Total Persons Monitored | 8225 |
| Average Committed Effective Dose (rem) | 0.004 |
| Highest Committed Effective Dose (rem) | 0.025 |
| **Phase 2: Open Availability Phase (Voluntary)<br>All scan results <MDA** | |
| Dependent Children/Infants Monitored | 51 (32%) |
| Dependent Adults Monitored | 46 (30%) |
| DOD Civilian Employees/Contractors | 38 (24%) |
| Active Duty Military | 20 (13%) |
| Total Persons Monitored | 155 |
| | |
| **Total Persons Monitored for Both Phases** | **8380** |

### D-4. Urine Bioassay

Some individuals with higher potential for exposure from internal contamination were monitored for intake of radioactive material by the collection of 24-hour, pre-deployment (baseline) and post-deployment urine samples for the purpose of performing in-vitro radioanalysis. These 24-h urine samples were collected using standard DOD procedures and were processed in the USAFSAM Radioanalysis Laboratory at Wright-Patterson AFB, OH. Due to the short half-lives of the radioiodines, which contribute major portions to dose and the longer than normal processing times at USAFSAM caused by personnel deployments to support OT response operations, urine bioassays were not an effective assay technique for assessment of intake and dose.

# Appendix E.

## Consolidated Listing of Assumptions for Dose Calculations

This appendix provides a consolidated set of assumptions used in performing the dose calculations.

### E-1. Scenario/Pathway Considerations

1. Pathways of exposure are assumed to be external radiation, inhalation of airborne materials, and ingestion of contaminated water and soil.
2. Food consumption was assumed to be an unimportant source of exposure.
3. DOD locations were consolidated based on distance and direction from the Fukushima Daiichi Nuclear Power Station.
4. Doses were calculated based on hourly increments of exposure, though some measurements did not have hourly resolution.
5. Doses are related to environmental measurement data

### E-2. Life Style Parameters

6. Human behavior characteristics used "upper percentile values" of EPA's Environmental Factors Handbook and supporting documents.
7. Adults, PEP Category 1 individuals, are assumed to have a daily inhalation rate of 30 cubic meters, four liters per day of water intake, and 200 mg per day of soil ingestion.
8. PEP Category 2 individuals (adult, humanitarian relief efforts) are assumed to have an inhalation rate of 32 cubic meters per day; a water intake rate of six liters per day, and a soil ingestion rate of 500 mg per day.
9. Children, PEP Category 3 individuals, are assumed to have age-dependent inhalation and water ingestion rates consistent with or exceeding ICRP and EPA recommendations. Inhalation rates range from 9.2 (3 month old) to 21.9 (15 year old) cubic meters per day. Drinking water ingestion rates range from 1.2 (3 month old) to 2.8 (15-year old) liters per day. The soil ingestion rate is set at 1,000 mg per day, consistent with the EPA's assumption for soil-pica.
10. Age-dependent times spent outdoor were derived from EPA guidelines and ranged from 1275 (10 year old) to 1440 minutes (3 month and one year old) per day.

### E-3. Dose from Inhalation of Airborne Material

11. Aerosols are characterized by a particle size distribution of 1-µm AMAD.
12. Barium used as a surrogate for surveillance of strontium isotopes in high volume air samples collected at Yokota AB for samples where isotopic strontium analyses were not performed.

13. Gaseous forms of all radioiodines in air samples in Kanto Plain were comprised of two-thirds organic iodine (methyl iodide) and one-third elemental iodine.

    Concentrations for unquantified radionuclides in some environmental measurements were inferred from scaled comparisons to Cs-137 in the sample in question and another sample taken at the same time with quantified results for the radionuclideDose conversion factors for airborne particulates assume the factor providing the greatest dose.

## E-4. Dose from Ingestion

14. Soil concentrations for days without measurements were derived by interpolation or decay correction, or interpolation of reported results.
15. For installations with multiple soil samples collected on the same day, the concentration for that measurement day used in dose calculations was based on the arithmetic mean of the reported concentrations for the day.
16. Dose estimates for ingestion of soil are based on the radionuclides: Cs-134, Cs-136, Cs-137, I-131, and Te-132. For samples with reported concentrations of those radionuclides that were below the detection level, various methods were used to estimate the activity. In some cases, relationships of a specific radionuclide with Cs-137 from other samples reported results for both the Cs-137 and the other radionuclide were used.
17. Individuals assigned to DOD installations were assumed to consume municipal water, although many DOD installations had groundwater sources with no detectable radiological impacts.
18. Ground-deposited radionuclides were decay-extrapolated back to March 12 for conservatism, although the majority of the deposition occurred between March 12 and 24.
19. For ground-deposited radionuclides, vertical migration of contaminants was deemed insignificant during the 60-day period covered in the report.

## E-5. Protective Factors

20. No credit was taken for the blocking effects of KI on absorption of radioiodines by the thyroid. USFJ issued initial guidance for Service members to take KI if they were within 100 nautical miles (nm) of FDNPS, based on a reasonable expectation of exposure to radioiodine. Subsequent USFJ guidance authorized issuance of KI to all DOD personnel and dependents. Although most individuals were never directed to take KI, there is anecdotal evidence that indicates that some of these people who did not enter the 100 nm radius did take the medication.

# Appendix F.

## External Radiation Dose Rate Data

### F-1. External Dose Rates for 13 DARWG Locations

Section 2.3 discusses measurements of external radiation dose rates conducted by DOD, DOE and GOJ organizations and considered in this analysis. The section describes the types of data available, some of the characteristics and limitations of those data, and describes the process for consolidating data from DOD and DOE with MEXT data adjusted to correspond to the nominal DOE/DOE levels.

This section contains plots of the exposure rate data used in dose calculations to demonstrate the contributions of consolidated DOD and DOE results, and adjusted results from the nearest MEXT station in the same prefecture. Location D-5 J-Village is not listed.

**Table F-1. Listing of external dose rate plots for 13 DARWG locations**

| DARWG Location Number and Name | Figure Link |
|---|---|
| D-1 Misawa AB | Figure F-1 |
| D-2 Sendai Airport | Figure F-2 |
| D-3 City of Ishinomaki | Figure F-3 |
| D-4 City of Yamagata | Figure F-4 |
| D-6 Hyakuri AB | Figure F-9 |
| D-7 City of Oyama | Figure F-6 |
| D-8 Yokota AB | Figure F-7 |
| D-9 Akasaka Press Center | Figure F-8 |
| D-10 Atsugi NAF | Figure F-9 |
| D-11 Yokosuka NB | Figure F-10 |
| D-12 Camp Fuji | Figure F-11 |
| D-13 Iwakuni MCAS | Figure F-12 |
| D-14 Sasebo NB | Figure F-13 |

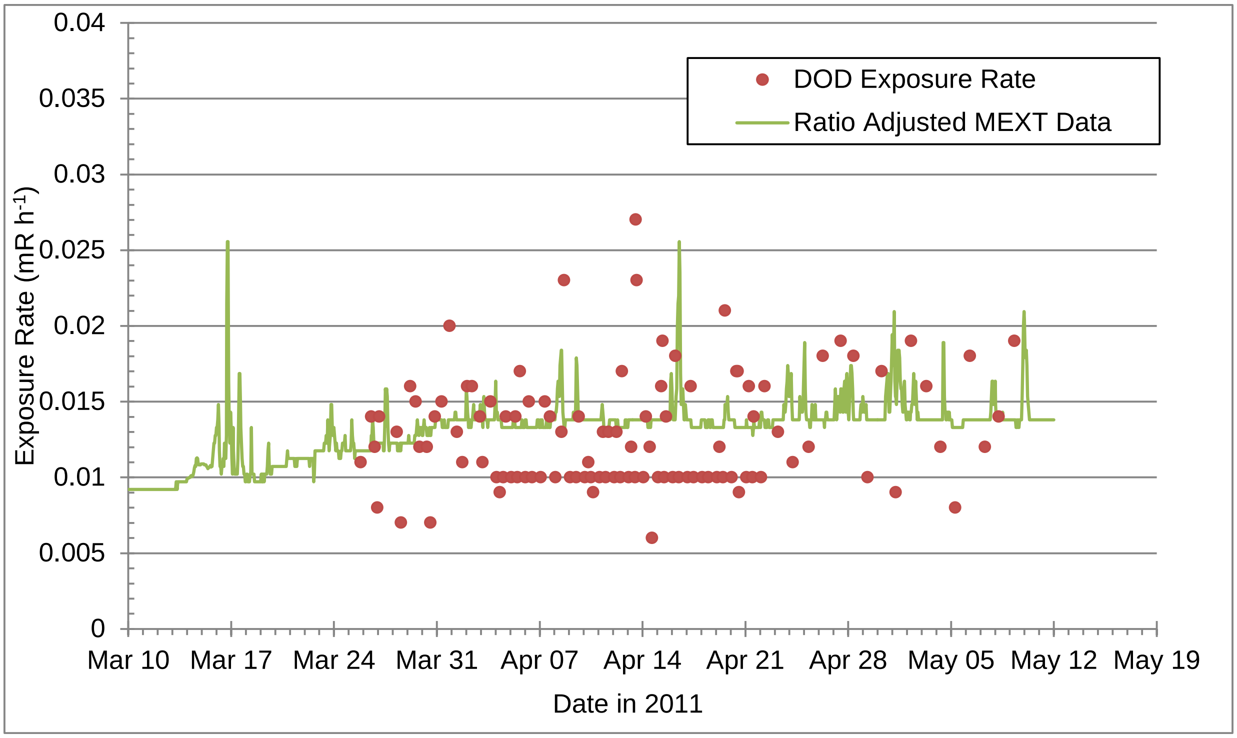


**Figure F-1. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-1 Misawa AB**

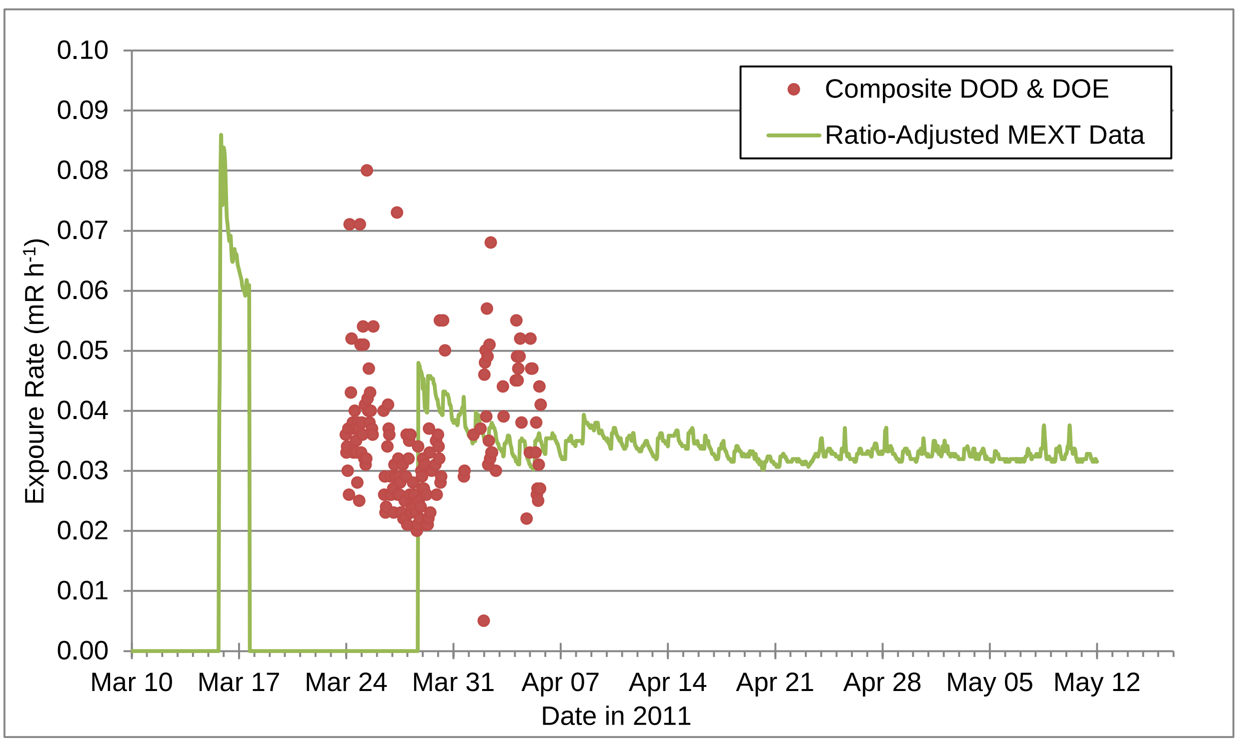


**Figure F-2. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-2 Sendai Airport**

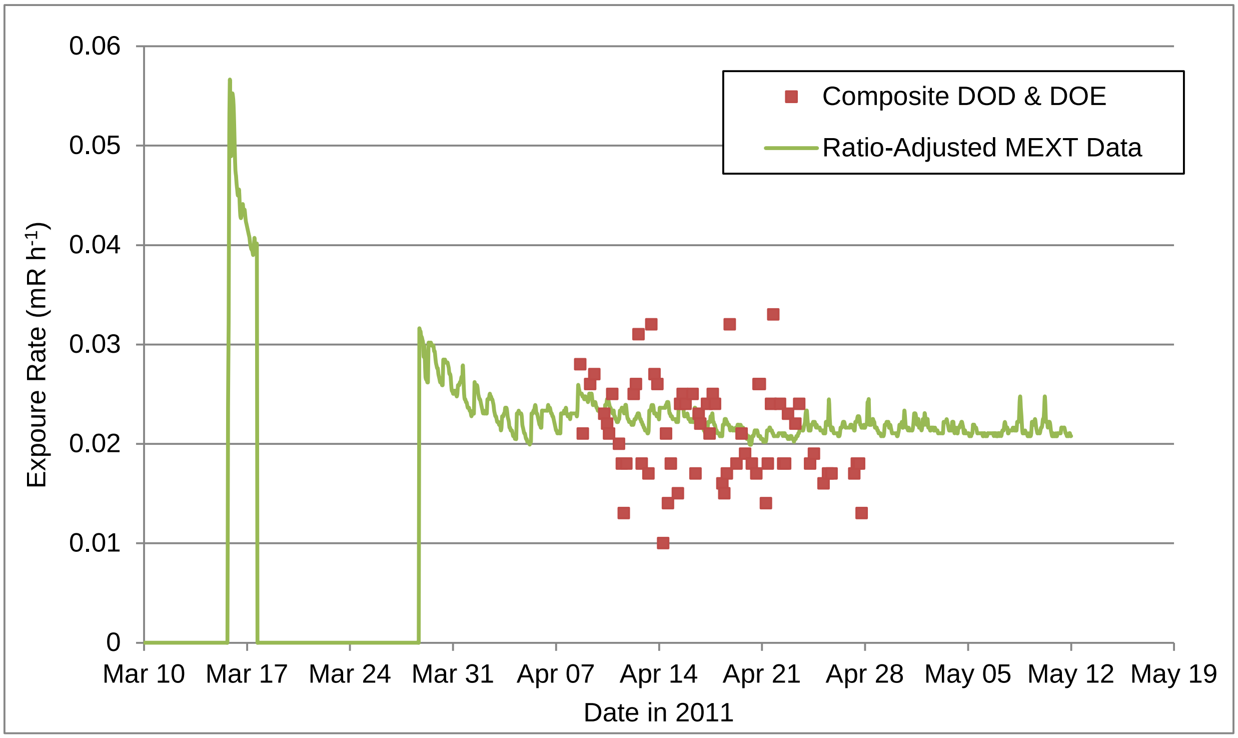


**Figure F-3. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-3 City of Ishinomaki**

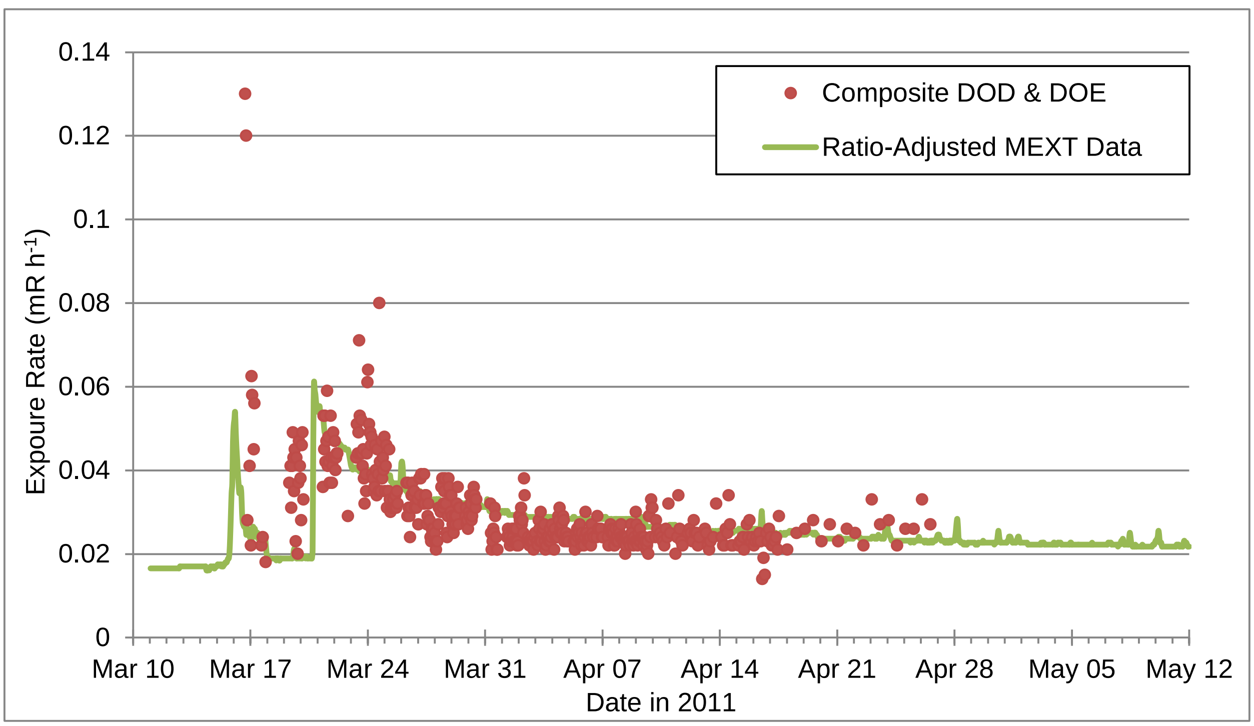


**Figure F-4. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-4 City of Yamagata**

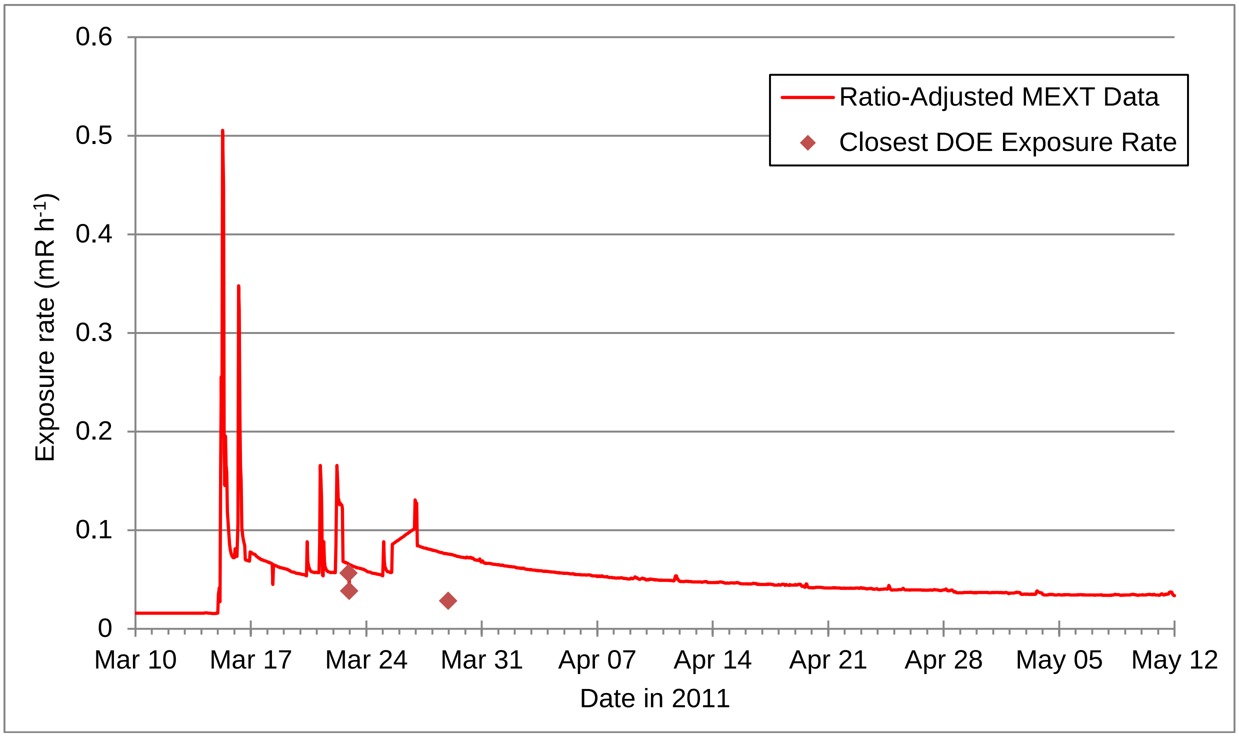


**Figure F-5. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-6 Hyakuri AB**

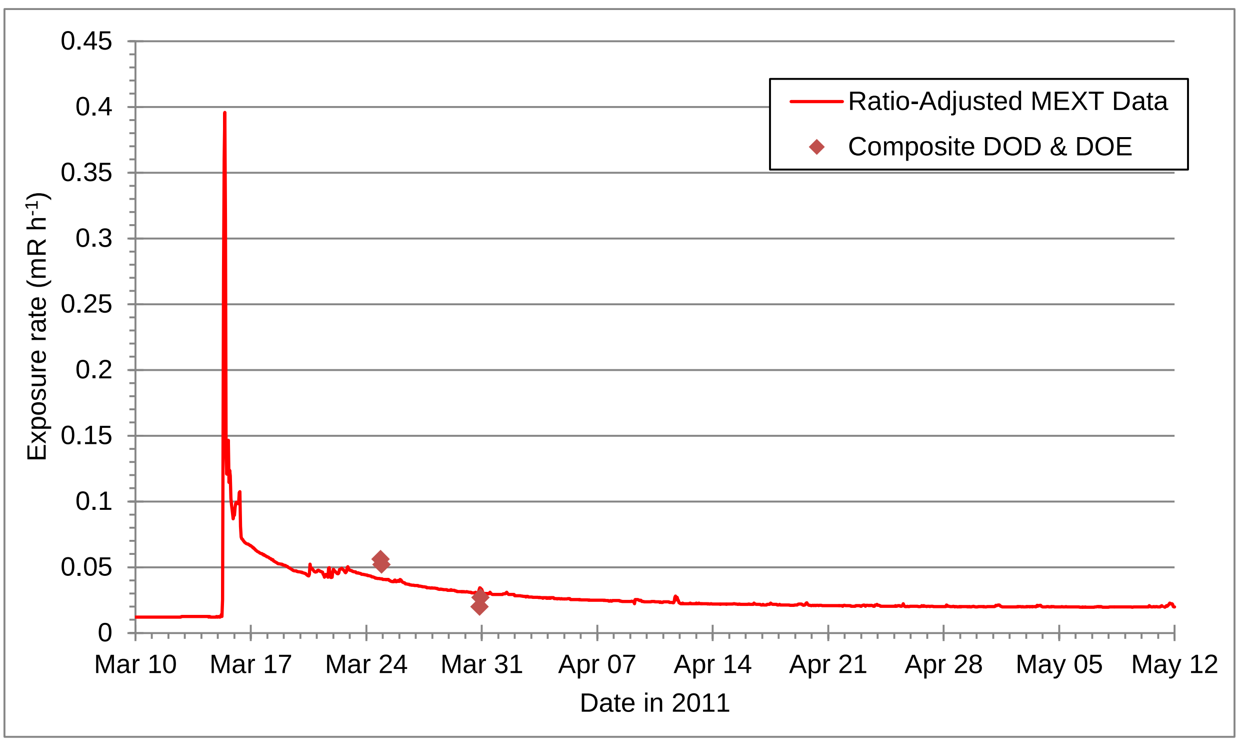


**Figure F-6. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-7 City of Oyama**

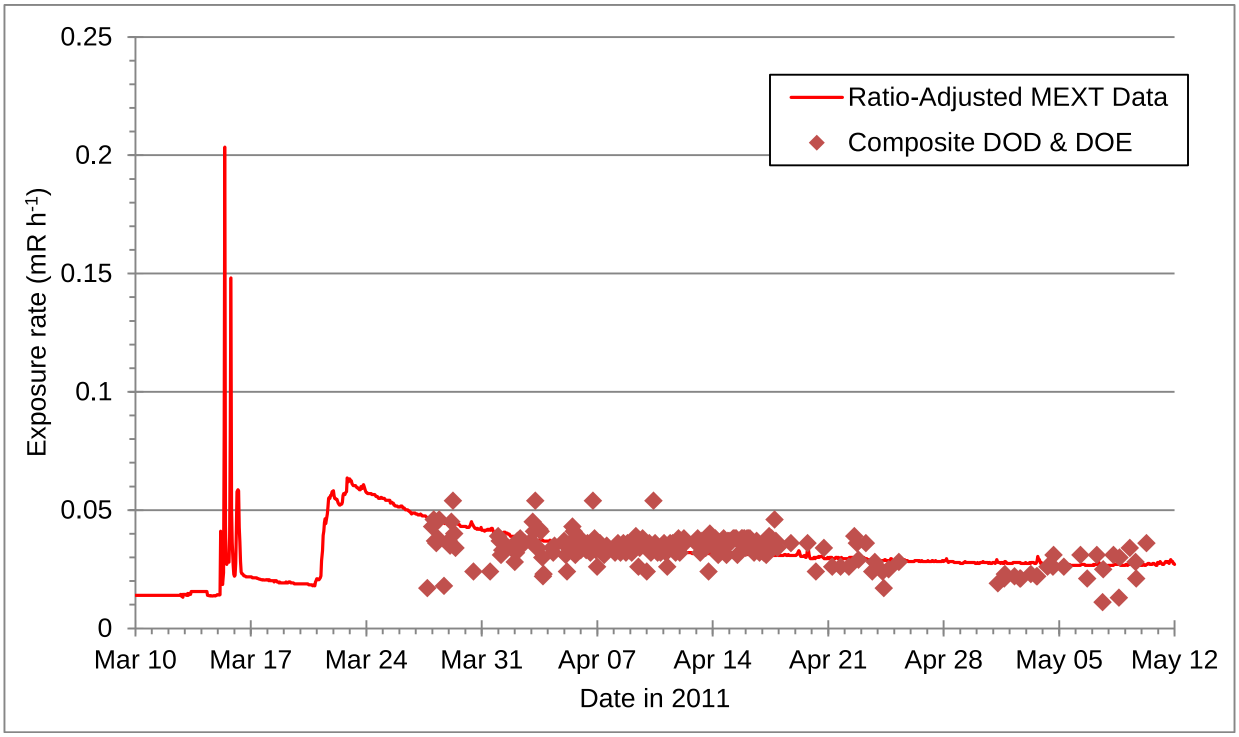


**Figure F-7. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-8 Yokota AB**

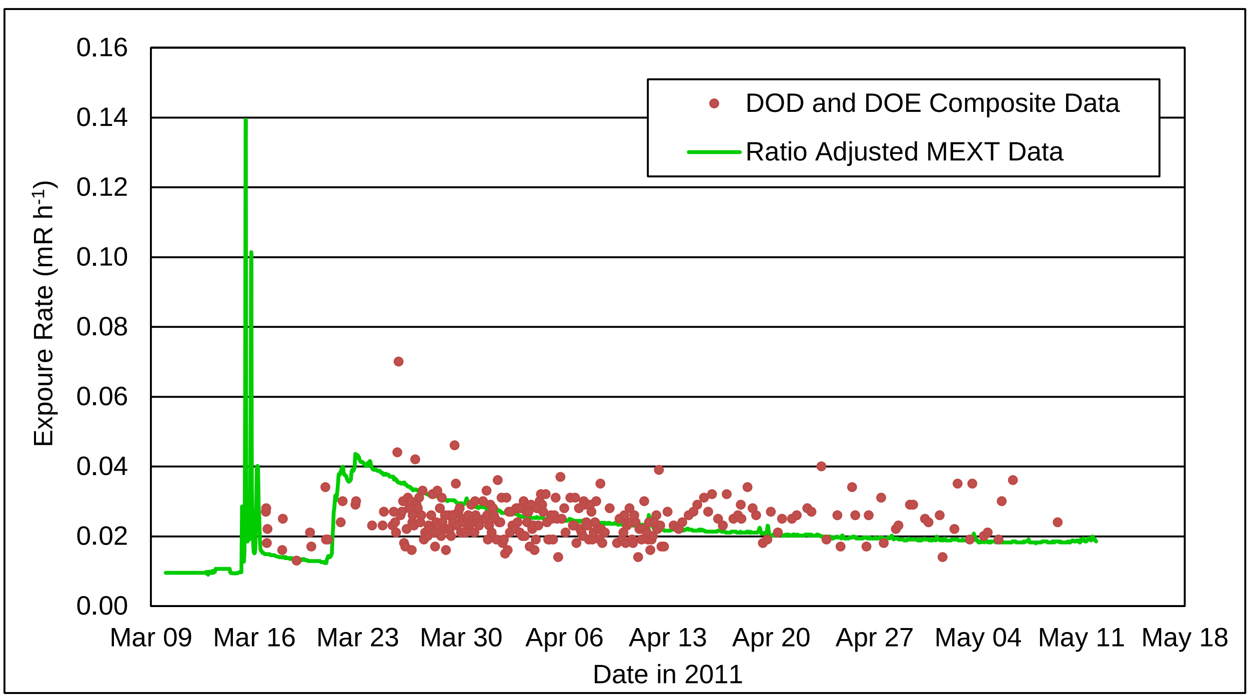


**Figure F-8. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-9 Akasaka Press Center**

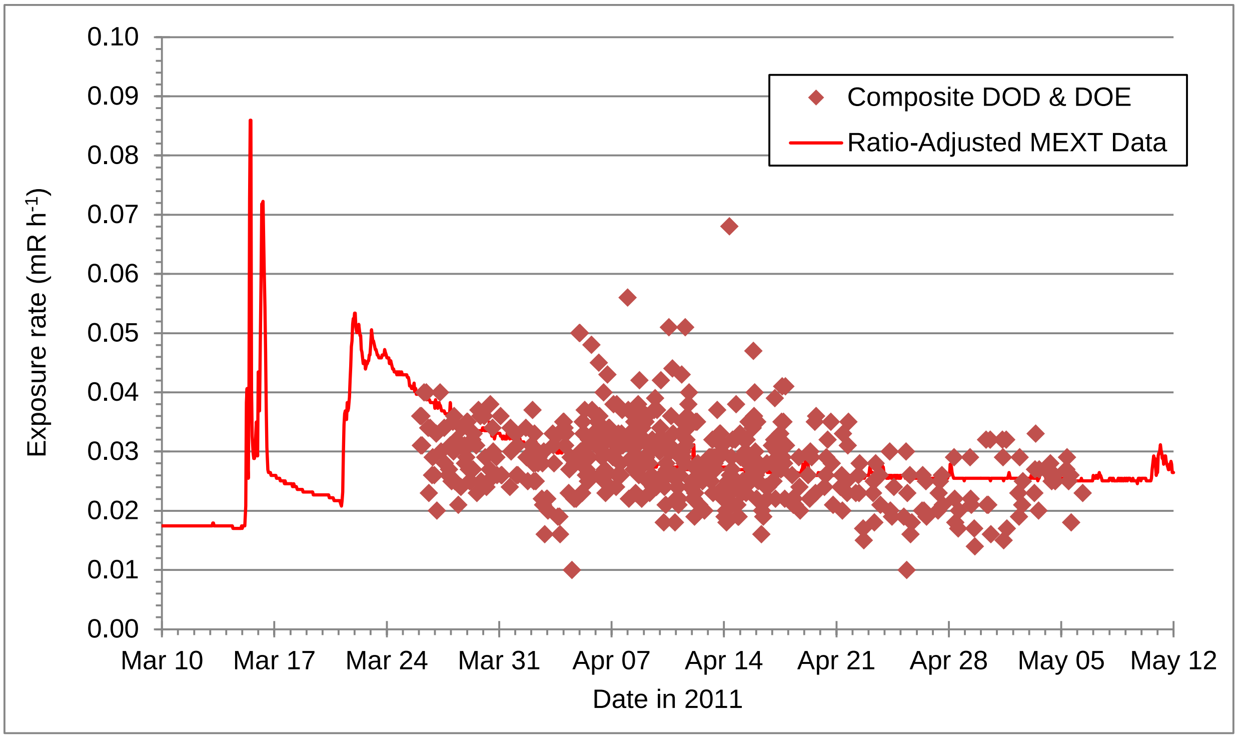


**Figure F-9. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-10 Atsugi NAF**

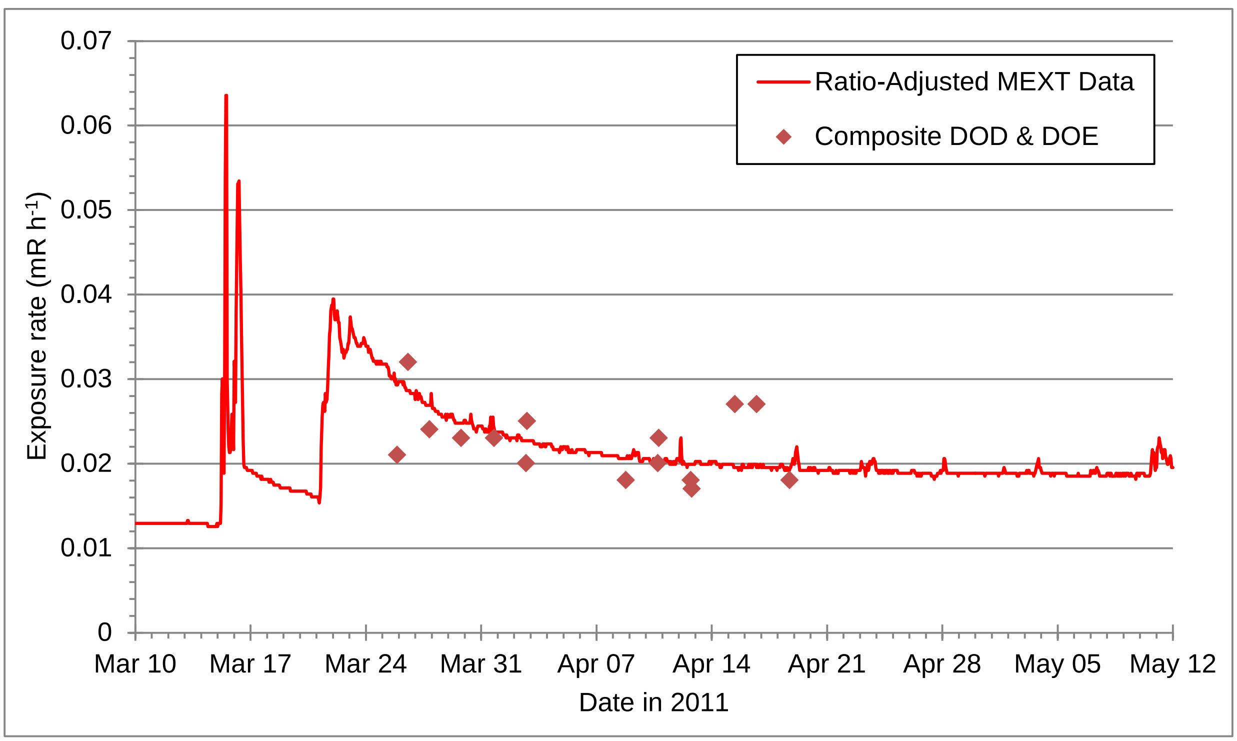


**Figure F-10. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-11 Yokosuka NB**

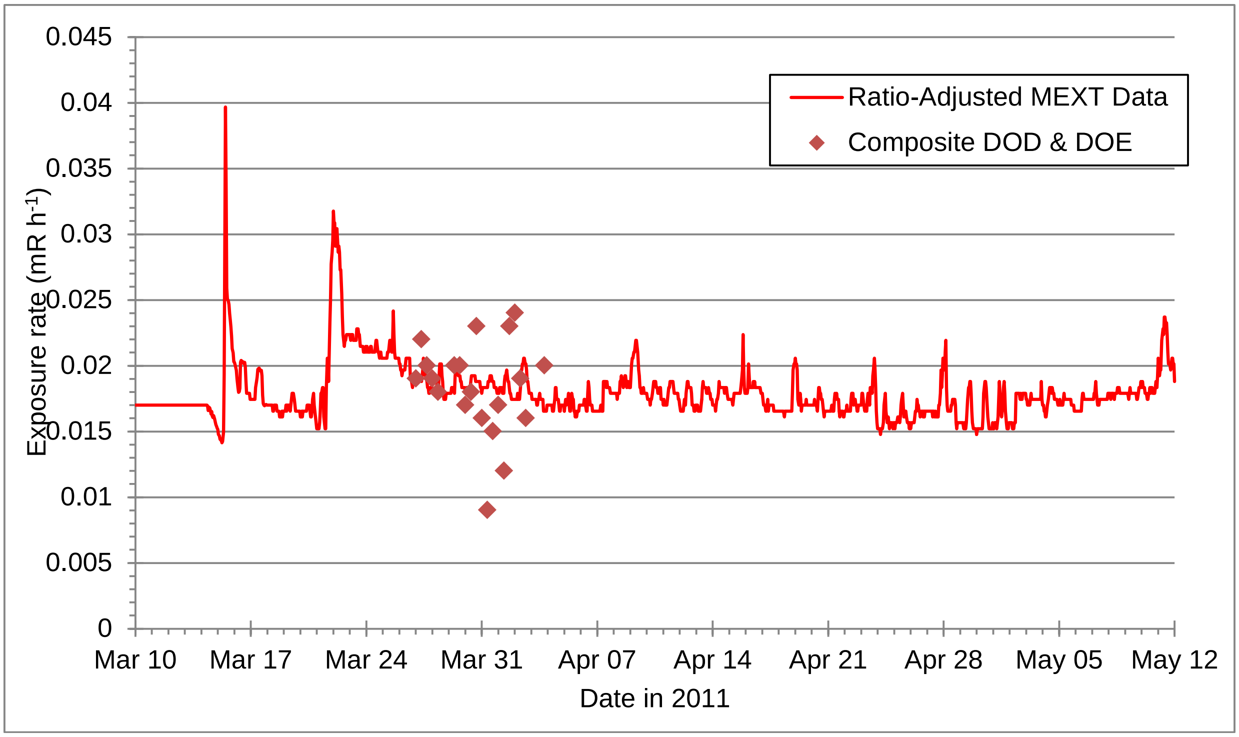


**Figure F-11. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-12 Camp Fuji**

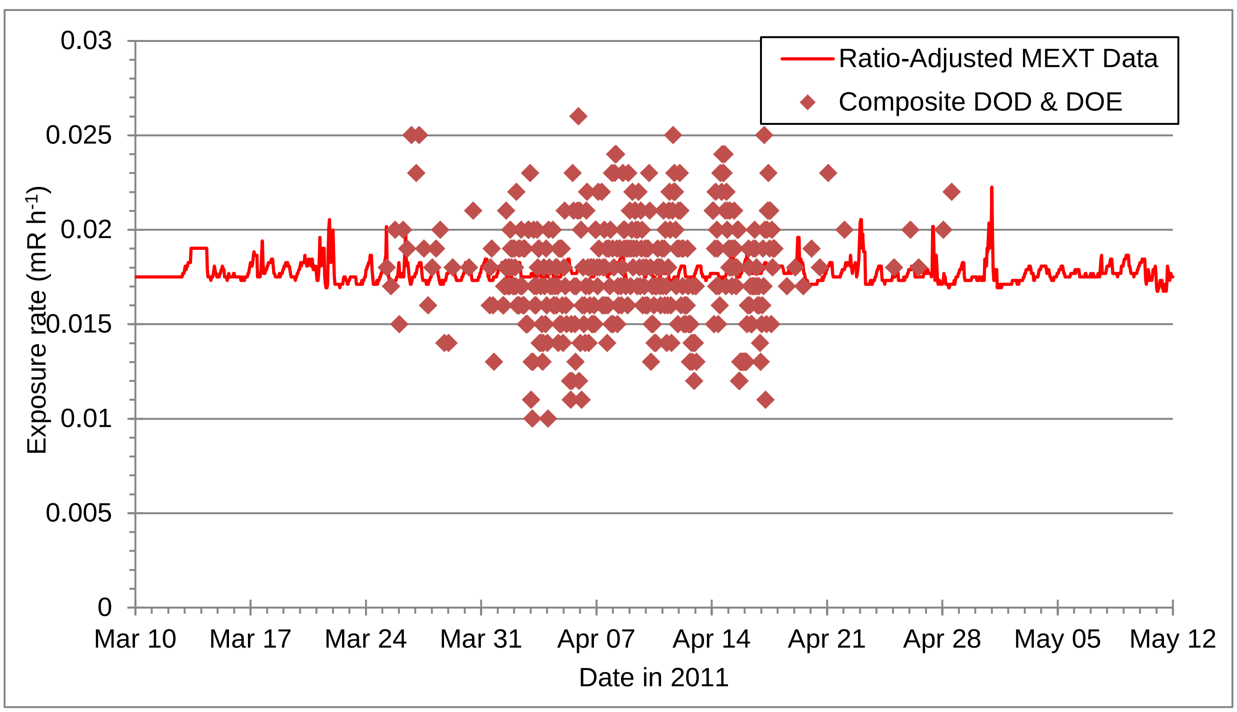


**Figure F-12. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-13 Iwakuni MCAS**

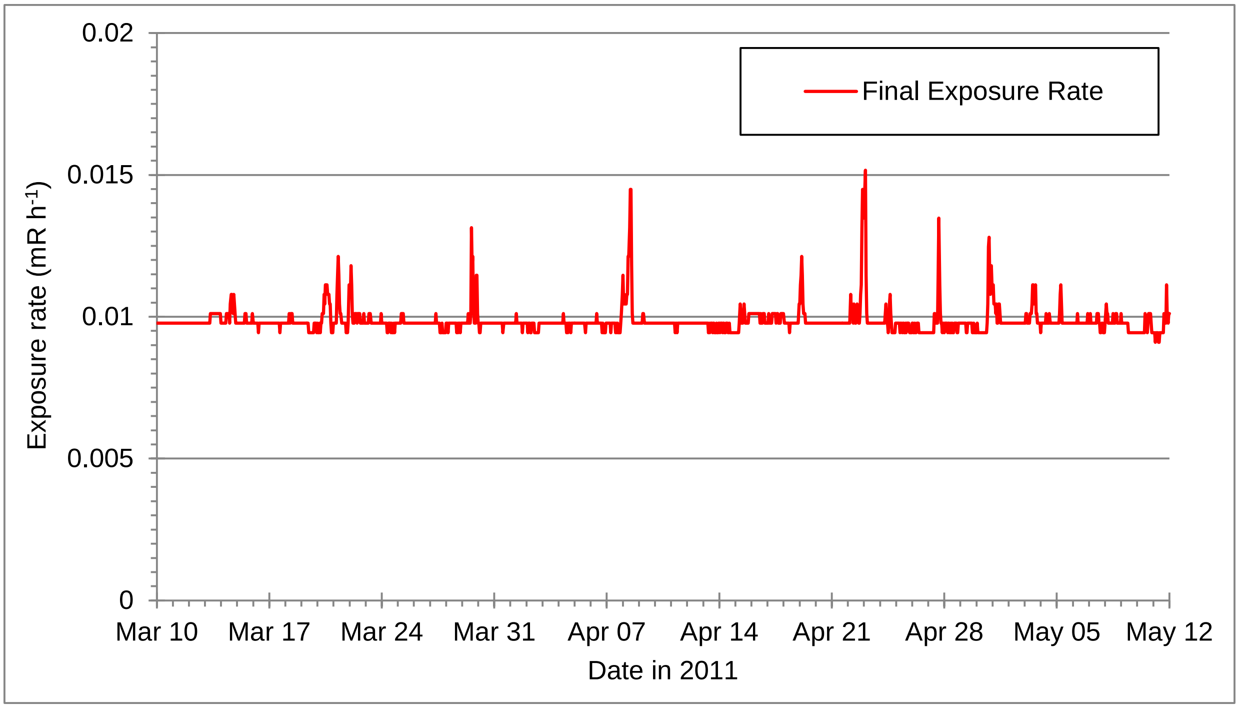


**Figure F-13. DOD and DOE composite plus adjusted MEXT exposure rates at DARWG Location D-14 Sasebo NB**

## Abbreviations, Acronyms and Symbols

| | |
|---|---|
| α | Alpha (radiation) |
| β | Beta (radiation) |
| Γ | Gamma (radiation) |
| µ | micro; as in µR (microroentgen) or µm (micrometer) |
| AB | Air Base |
| AC | Alternating Current |
| ADM | Admiral |
| AFB | Air Force Base |
| AFRAT | U.S. Air Force, Radiation Assessment Team |
| AFRRI | Armed Forces Radiobiology Research Institute |
| AIPH | U.S. Army Institute of Public Health |
| ALFOODACT | DOD's All Food & Drug Act |
| AMAD | Activity Median Aerodynamic Diameter |
| atm | atmosphere |
| ASD(HA) | Assistant Secretary of Defense for Health Affairs |
| BE | U.S. Air Force, Bioenvironmental Engineering |
| Bq | becquerel |
| cm | centimeter |
| CPG | Compliance Policy Guide |
| COMPACFLT | Commander, Pacific Fleet |
| CONUS | Continental United States |
| CV | Coefficient of Variation |
| DARWG | Dose Assessment and Recording Working Group |
| DC | Dose Coefficient |
| DeCA | Defense Commissary Agency |
| DFARS | Defense Federal Acquisition Regulations Supplement |
| DIL | Derived Intervention Level |
| DLA | Defense Logistics Agency |
| DMDC | Defense Manpower Data Center |
| DOD | Department of Defense |
| DOE | Department of Energy |
| DRFE | Dose Reduction Factor for External Radiation |
| DRFI | Dose Reduction Factor for Inhalation |
| DTRA | Defense Threat Reduction Agency |
| DWPE | Detain without Physical Examination |
| E | Effective Dose |
| EDE | Effective Dose Equivalent |
| EFH | Exposure Factor Handbook |
| EPA | Environmental Protection Agency |
| F | Type F (Fast rate of absorption) |
| FADL | DOD Food Analysis & Diagnostic Laboratory |
| FDA | Food & Drug Administration |
| FDNPS | Fukushima Daiichi Nuclear Power Station |
| ft | foot |
| g | gram |
| G-M | Geiger-Mueller |
| GOJ | Government of Japan |

| | |
|---|---|
| Gy | gray; the SI unit of absorbed dose |
| h | hour |
| HADR | Humanitarian Assistance / Disaster Relief |
| IAEA | International Atomic Energy Agency |
| ICRP | International Commission on Radiological Protection |
| IDRFE | Indoor Dose Reduction Factor for External Radiation |
| IDRFI | Indoor Dose Reduction Factor for Inhalation |
| IM | Internal Monitoring |
| IMS | International Monitoring Station |
| INES | International Nuclear and Radiological Event Scale |
| IRF | Intake Retention Factor |
| JDVC | Japan District Veterinary Command |
| JPY | Japanese Yen |
| JSDF | Japanese Self Defense Force |
| JST | Japan Standard Time |
| keV | kiloelectron volt |
| kg | kilogram |
| km | kilometer |
| L | liter |
| LANL | Los Alamos National Laboratory |
| Lt Gen | Lieutenant General (USAF) |
| m | meter |
| M | Type M (Moderate rate of absorption) |
| MAFF | Japanese Ministry of Agriculture, Forestry, and Fisheries |
| M&CUWG | Medical and Claims Users Working Group |
| MCAS | U.S. Marine Corps Air Station |
| MDA | Minimum Detectable Activity |
| MDC | Minimum Detection Concentration |
| MEF FWD | Marine Expeditionary Force, Forward |
| MeV | megaelectron volt |
| MEXT | Japanese Ministry of Education, Culture, Sports, Science, and Technology |
| min | minute |
| mg | milligram |
| mo | month |
| NAF | Naval Air Facility |
| NAS | National Academy of Science |
| NB | Naval Base |
| NCRP | National Council on Radiation Protection & Measurements |
| NISA | Nuclear and Industrial Safety Agency (Japan) |
| NNSA | National Nuclear Security Administration |
| NORM | Naturally Occurring Radioactive Material |
| NUREG | A series of Nuclear Regulatory Commission guidance publications |
| NVLAP | National Voluntary Laboratory Accreditation Program |
| OSL | Optically Stimulated Luminescence |
| OT | Operation Tomodachi |
| OTR | Operation Tomodachi Registry |
| OTRIWG | OTR Implementation Working Group |
| pCi | picocurie |
| PEP | Potentially Exposed Population |
| PHCR-PAC | U.S. Army, Public Health Command Region-Pacific |

| | |
|---|---|
| POI | Population of Interest |
| POIWG | Population of Interest Working Group |
| POL | Petroleum, Oil, and Lubricant |
| rad | Conventional unit of absorbed dose |
| RADIAC | Radiation Detection, Identification, & Computation |
| rem | Conventional unit of equivalent dose roentgen equivalent man |
| SFP | Spent Fuel Pool |
| SI | International System of Units |
| Sv | sievert; the SI unit of equivalent dose |
| SVAC | Senate Veterans' Affairs Committee |
| T | tissue or organ |
| TED | Total Effective Dose |
| TEPCO | Tokyo Electric and Power Company |
| USA | United States Army |
| USAF | United States Air Force |
| USAFSAM | U.S. Air Force, School of Aerospace Medicine |
| USC | United States Code |
| USD | U.S. Dollar |
| USD(P&R) | Under Secretary of Defense for Personnel and Readiness |
| USFJ | U.S. Forces, Japan |
| USG | United States Government |
| USMC | United States Marine Corps |
| USN | United States Navy |
| USPACOM | U.S. Pacific Command |
| USPACFLT | U.S. Pacific Fleet |
| WEAC | Winchester Engineering Analytical Center |
| WHO | World Health Organization |
| y | year |